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SUMMARY REPORT

30 June 1963 - 30 June 1964
NASA CONTRACT NAS8-5451
DEVELOPMENT OF SENSOR
TO MEASURE HOT GAS LEAKS
FROM FLANGES AND SEALS
IN PLUMBING OF SATURN VEHICLE

REC REPORT 7648 Rev. A

Date 8 July 1964

Prepared for: George C. Marshall Space Flight Center, Huntsville, Alabama

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Authors: (Sathyakumar, Johnson, Domich)

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	43		Added Figure 16		
	44		Added Figure 17		
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Final Report On

DEVELOPMENT OF HOT GAS LEAK SENSOR

30 June 1963 - 30 June 1964

REC Report 7648

SUMMARY. A Rosemount Engineering Company mass flow sensor in a specially designed package meets the rigorous requirements of NASA Contract NAS8-5451. This contract is entitled "Development of a Transducer to Measure Hot Gas Leaks from Flanges and Seals in Plumbing of the Saturn Vehicle." The primary problem was the thermal isolation of the sensing element and the electronics from the high temperatures of the gases and the environment. The required isolation from the temperature of the gases is obtained by an annular, counterflow heat exchanger system. The required isolation from the environmental temperature is obtained by insulation and by low-conductive attachment of the sensing element and electronics to the base of the unit. The low temperature requirement is accommodated by the use of controlled heaters on the gas heat exchanger and on the electronics package.

Vibration requirements are met or exceeded through proper mechanical design of the components and their assemblies.

1. INTRODUCTION. Conventional leak sensors (or mass flow sensors) are not suited for measurement of hot gases of combustion primarily because of the high temperatures involved. The approach taken here is to use a standard mass flow sensor and package it so that the temperature effects are minimized.

This report will delineate the requirements, discuss the general approach taken and describe the specific designs of the various components. Problems and their solutions are discussed. Experimental tests, and new technology are described. The finalized specifications are then given.

2. REQUIREMENTS. Leaks from flanges and seals in the plumbing of the Saturn Vehicle will be directed through a leak measuring transducer and then overboard. The transducer must meet the requirements and withstand the environments listed below.

1. Gases to be Measured:
   Liquid Oxygen - RP-1 combustion products.
   Liquid Oxygen-Liquid Hydrogen combustion products.
2. Temperature of Gases:
   LOX-RP1: 650°C to 925°C.
   LOX-LH_2: 400°C to 705°C.
3. Ambient Temperature of Transducer: -155°C to +75°C normally with an exposure to +815°C for 5 minutes.
4. Ambient Pressure: 700 mm Hg to 10^{-3} mm Hg.
5. Flow Rate:
   0 to 1000 standard cubic centimeters per minute, and
   0 to 200 standard cubic centimeters per minute.
6. Output:
   0 to 5.5 millivolts for 0 to 200 std cc/min.
   0 to 10 millivolts for 0 to 1000 std cc/min, and continuously increasing from 200 Std cc/Min. to 1000 Std cc/Min. Output Impedance shall be less than 500 ohms.
7. Power: 9 watts or less.

8. Input: 28 ± 3 volts DC.

9. Physical Size: Less than 60 cubic inches and 2 lbs.

10. Time Response: 700 milliseconds or less for a 63.2% step change in input flow rate.

11. Vibration: a) Random noise with a band width of 20 to 2000 cps.

b) Random noise motion of 26.0 g RMS for 4 seconds and 16.0 g RMS for a period of 180 seconds.

12. Accuracy: ± 5% full scale.

13. Attitude: Insensitive to attitude change.

14. Calibration: The transducer shall have a calibration curve that is valid under any one or all of the environmental conditions set forth above.

15. Back Pressure: Less than 8 psi.

16. Craftmanship: In accordance with

a) ABMA-STD-428B

b) MSFC-PROC-158A

c) MIL-I-6181D (RFI)

17. Electrical Connector: Bendix 72-74114-5P or equivalent.

18. Pneumatic Connections: Standard MF 1815C04.

The above requirements reflect the changes that have occurred during the program.

19. Warm up time shall be less than 20 minutes.

3. GENERAL APPROACH. After consideration of the problem involved, we decided the best solution was to adapt our existing mass flow sensor to the requirements stated. This decision left two major problems to be solved. The gas entering the sensing element must be preconditioned and the sensing element and the electronics package must be protected from high environmental temperatures.

The sensing element can inherently withstand a considerable portion of the required temperature range. The electronics package was designed to also operate within the sensor range. These facts somewhat eased the problems by reducing the amount of heat to be protected against.

The incoming gas is preconditioned by an annular, counterflow heat exchanger. The environmental temperature range is accommodated by insulation, size of the outer housing and a low heat conduction attachment of the sensor and electronics to the external surface of the transducer. Heaters on the sensing element and on the electronics take care of the required low temperature ranges.

4. SENSOR DESIGN.

4.1. Definition of Design Problem. The design problem was to adapt the REC sensor to meet the severe environmental requirements. The major items requiring solution were:

1. To provide high temperature environment protection for the electronics package and sensing element.

2. To thermally precondition the gas entering at up to 900°C to the operating temperature of the leak sensing device.

3. To heat, with the allowed power, the electronics package and the sensor assembly to 0°C or above when the ambient temperature dropped below 0°C.

4.2. Gas Preconditioner Design.

4.2.1. Design Goal. The requirements of the gas preconditioner are:

1. Limit the temperature (up to 900°C) of the incoming gas to 100 ± 50°C when it enters the sensing element.

2. Maximum efficiency.

3. Minimum weight and size.

4. Minimum pressure drop.

4.2.2. Design. To meet the requirements of size and good vibration capabilities, a counterflow type of heat exchanger was decided upon as shown on the interior construction drawing, (Fig. 1).

4.2.2.1. Assumptions. The gas properties were assumed to be the same as carbon dioxide. This constituent of the combustion products of RP-1 fuel and liquid oxygen has the highest density and specific heat and hence would have maximum heat rejection. By making this assumption, we arrive at a conservative length for the heat exchanger. The mass flow rate is assumed to be 1000 std cc/min for the following calculations. A convenient tube with an internal diameter of 0.1016 cms and a wall thickness of 0.0508 cms is used in the calculations.

4.2.2.2. Calculations. To determine the length of a counterflow type of heat exchanger, the following must be calculated.

1. The inner film coefficient h_1

2. The heat transfer coefficient through the tube wall, h_2

3. The outer film coefficient, h_3

4. The average heat transfer coefficient, h_{av}

5. The heat rejection rate, Q

The choice of the proper equation for the inner film coefficient determination depends on the type of flow; turbulent or laminar.

The flow is turbulent if the Reynolds Number is greater than 6000. We must therefore first determine the Reynolds Number, Re. Using the equation

$$\mathcal{V} = \frac{4}{60} V/\pi d^2 \qquad (1)$$

where $\mathcal{V}$ = Velocity in cm/sec

V = Volumetric flow rate = 2258.4 cc/min at gas temperature of 700°K.

π = Constant 3.142

d = The internal diameter = 0.1016 cms

the velocity of the gas flowing through the tube was determined to be 4642.11 cms/sec.

The Reynolds Number was calculated using the following equation, (Ref. 2):

$$Re = (\rho \times \mathcal{V} \times d)/\mu \qquad (2)$$

where Re = Reynolds Number

*ρ = Density .000766 gms/cc at 700°K

$\mathcal{V}$ = Velocity = 4642.11 cm/sec

d = Internal diameter, 0.1016 cms

*μ = Viscosity = 0.000242 poise.

The Reynolds Number, Re, = 14.9287×10^3. Since the Reynolds Number is much higher than 6000, we can positively assume that the flow is turbulent through the tube.

The inner film coefficient, h_1, is determined by the equation (Reference 3):

$$h_1 = (Nu_d \times K)/d \qquad (3)$$

where h_1 = The inner film heat transfer coefficient

Nu_d = The Nusselt Number

K = The thermal conductivity of the gas; and

d = Internal tube diameter.

* The values are considered at this mean average temperature of 700°K.

The Nusselt Number is determined by the following equation (Reference 1) for turbulent flow:

$$\frac{Nu_d}{Re_d\ Pr} = \frac{0.0396\ (Re_d)^{-1/4}}{1 + A\ (Re_d)^{-1/8}\ (Pr-1)} \qquad (4)$$

where Re_d = Reynolds Number = 16.8968×10^3

Pr = Prandtl Number = 0.670 (Value given for carbon dioxide at 700°K)

A = $1.5\ Pr^{-1/6}$ = 1.47 at 700°K

This gives Nu_d = 41.7679

Using this value in Equation (3) as well as the following:

K = 0.0005 watts/cm°K at 700°K

and d = 0.1016 cm

we determine the inner film coefficient, h_1, to be .2051131 watts/°K cm^2.

The heat transfer through the tube wall is found by using the following equation (Ref. 1):

$$h_2 = \frac{K}{l_n\ (r_o/r_i)\ r_o} \qquad (5)$$

where h_2 = Heat transfer coefficient through tube wall

K = Thermal conductivity of the material of the tube = 0.163 watts/cm °K,

r_o = Outside radius in cms = 0.1,24 cms, and

r_i = Inside radius in cms = 0.1016 cms.

The resulting heat transfer coefficient, h_2, = 25.958 watts/°K cms^2.

The determination of the outer film coefficient again depends on whether the flow is laminar or turbulent. We therefore must determine the Reynolds Number. Using Equation (2) since the velocity is the same, we can calculate the Reynolds Number for the outside diameter of 0.1524 cms. This gives a Reynolds Number = 25.345×10^3. This again is positively turbulent flow and hence the outer film coefficient can be calculated using the following equation (Ref. 1):

$$h_3 = \frac{0.0296\ \rho\ C_p\ \mathcal{V}_s\ (Re)^{-0.2}}{1 + 2.12\ Re^{-0.1}\ A\ (Pr-1)} \qquad (6)$$

ρ = Density = 0.000766 gm/cm^3 at 700°K.

C_p = Specific heat = 1.05 watt sec/gm°K at 700°K.

Re = Reynold Number = 22.393×10^3

Pr = Prandtl Number = 0.67 at 700°K

$\mathcal{V}_s$ = Velocity = 4642.11 cms/sec

$A = 1.5\ Pr^{-1/6} = 1.47$

The solution of Equation (6) gives:

h_3 = 0.0239978 watt/°K cm^2

The average heat transfer coefficient can now be calculated using the following equation (Reference 1):

$$1/h_{av} = 1/h_1 + 1/h_2 + 1/h_3 \qquad (7)$$

h_{av} = .015125 watt/°K cm^2

The quantity of heat rejected, Q_1, by the gas per degree Kelvin temperature difference (Reference 1):

$$Q = (V\rho C_p)/60 \qquad (8)$$

where V = Volume flow rate = cc/min = 2258.4

ρ = Density gm/cc = .000766 at 700°K

C_p = Specific heat = 1.05 watt sec/gm °K at 700°K

Solving Equation (8) gives

At 700°K Q = 0.30273 with conditions at 700°K

Using these values in the following equation, (Ref. 1):

$$Q = h_{av} \pi dL \qquad (9)$$

where d = Tube diameter

L = Tube length

we obtain a length L for the heat exchanger = 6.27 at 700°K.

A length of 30 cm was chosen because it was convenient to spiral the heat exchanger within the housing of the sensor (Fig. 1).

The pressure drop for the heat exchanger was estimated using the following equation for turbulent flow through tubes. (Ref. 3):

$$\Delta_p = 0.078502 \times 10^{-9} (V^2 \rho)/d^5 \qquad (10)$$

where Δ_p = Pressure drop in pounds per square inch

V = Flow rate = 2258.4 cc/min.

ρ = Density at standard conditions = .000766 gm/cc

d = Internal diameter = 0.1016 cms.

This gives Δ_p = 0.84 pounds per square inch.

This is the pressure drop for one pass as this is a counterflow type heat exchanger. The gas passes through twice and hence the total pressure drop equals two times the calculated value or 1.68 lbs/sq inch.

4.3. Thermal Isolation. The electronics package and the sensing element must be protected from a 5-minute exposure of the complete unit to an external temperature of 815°C. The solution of this problem was to provide enough thermal lag between the outside of the case and the inside critical components so that the temperature of the components inside would be within the operating specifications.

The calculations were based on the fact that the external surface of the sensor package would be heated by free convection. The maximum cylinder diameter that would fit within the mounting hole dimensions is 3.5 inches. The calculations consist of determining the average heat transfer coefficient to the package (Ref. 1) and from that, the Biot Number (Ref. 4). Using the temperature response charts (Ref. 4), the time duration required to raise the temperature of the critical components to 125°C when the ambient temperature is suddenly raised to 815°C from room temperature was determined.

The average free convection heat transfer for a cylinder lying horizontally can be estimated by considering it as a vertical wall of length 2.5 times the diameter and then multiplying the heat transfer obtained by 4/3 (Ref. 1).

The cylinder diameter is 3.5 inches and hence calculations will be made for a vertical wall of 8.75 inches using the following equation, (Reference 1):

$$Gr = \frac{g \beta \nu_w x^3}{\nu^2} \tag{11}$$

where
- Gr = Grashof Number
- g = Acceleration of gravity = 32.2 ft/sec^2
- β = Expansion coefficient = $1/T_e$
- ν = Kinematic viscosity 147.8 ft^2/sec (Value from Ref. 1)
- ν_w = The temperature difference between the boundary layer and ambient = (1500–70)°F.

$$x = 8.75/12 \text{ ft}$$

This gives a Grashof Number = 1547.7006×10^4.

The boundary layer is laminar because the Grashof Number is less than 4×10^8 and hence we can use the following equation to determine the boundary layer thickness. (Reference 1).

$$\frac{\delta}{x} = 3.93\ Pr^{-1/2}\ (0.952 + Pr)^{1/4}\ (Gr)^{-1/4} \qquad (12)$$

δ = Boundary layer thickness, 0.076635 ft.

Pr = 0.706 (From Ref. 1)

Now using the following equation, with K = 0.0181 BTU/hr ft °F the heat transfer coefficient can be calculated. (Reference 1)

$$h = \frac{2\,K}{\delta} = \frac{0.0181 \times 2}{0.076635} = 0.472368 \text{ BTU/hr ft}^2\ ^\circ\text{F} \qquad (13)$$

The average heat transfer = $4/3\ h$ = 0.625824 BTU/hr ft^2 °F.

The Biot Number = $(h \times r)/K$ = 1.4 (14)

where h = Heat transfer = 0.625824 BTU/hr ft^2 °F

r = Radius in ft = 1.75/12

K = Thermal conductivity = 0.0625 BTU/hr ft^2 °F for a Q-felt insulation.

To use the temperature response charts we must have the dimensionless temperature ratio which is the allowed temperature rise over the actual temperature rise. The allowed temperature rise is 125°C and the actual external temperature rise is 815°C. Therefore, the dimensionless temperature number = 125/815 = 0.156. Using the temperature response chart in Reference 4 of a cylindrical shell of radius 1.75 insulated at its interal surface at r = 0.75" and exposed suddenly to a uniform temperature convective environment at 815°C at r = 1.75", we obtain a Fourier Number of 0.12 for a temperature ratio of 0.156 and Biot Number 1.4. To determine the time, we use the following equation, (Reference 4):

$$\text{Fourier Number} \qquad Fo = (\alpha\theta)/r_e^2 \tag{15}$$

where α = Thermal diffusivity = $K/(\rho C_p)$ (16)

θ = Time

r = Cylinder radius

K = Thermal conductivity of insulation = 0.0625 BTU/hr -ft -°F.

ρ = Density = 9 lbs/cu ft.

C_p = Specific heat = 0.2865 BTU/lb °F

α = 0.02425 ft^2/hr

r_e = 1.75/12 ft.

We therefore obtain a time

$$\theta = (Fo\ r_e^2)/\alpha \times 60 = 6.31 \text{ minutes.}$$

This calculation is based on the fact that it is perfectly insulated from the ends of the cylinder. This estimation is a guidance for the feasibility of the idea and experimental verification was carried out as discussed in the next section.

4.4. High Temperature Environment Test. This test was set up to study the temperature rise of the electronic package and the flow sensing element when the ambient temperature was suddenly increased to a higher value. Thermocouples made of 0.005 diameter chromel and alumel wire were mounted on the surfaces marked 1, 2, 3, and 4 as shown in Figure 2. The thermocouple outputs were monitored using the equipment as shown in Figure 3. The temperature of these surfaces were monitored every 15 seconds from the time the package was placed inside a high temperature oven with a hot convective atmosphere (air blowing at 135 ft per minute). The result obtained by this test would give us a conservative estimate of the temperature rise inside the package in the case of a still surrounding.

The test was performed in three stages:

1. First the step change was from room to 500°C. The data obtained by this experiment is shown in Figure 4. At the end of 300 seconds, the temperature of Surface 1 was 135°C, Surfaces 2 and 3 were 96°C, and Surface 4 was 130°C.

2. Second, the step was room temperature to 600°C. The results obtained for this run are shown in Figure 5. The temperature reached at the end of 300 seconds by the Surfaces 1, 2, 3, and 4 respectively are 225°C, 97°C, 90°C, and 307°C.

3. Third, the step was from room to 700°C. The results obtained by this test are shown in Figure 6. The temperature reached at the end of 300 seconds of Surfaces 1, 2, 3, and 4 respectively are 312°C, 190°C, 200°C, and 267°C.

The Surfaces 1, 2, and 3 are the ones inside which the package is located and these surface temperatures were much higher than their designed value of 125°C.

From the above discussed results, it was obvious that a redesign was necessary. A review of the design showed that most of the heat was being conducted up through the mounting structure. A redesign was made reducing the area of contact with the baseplate. This redesign structure is shown in Figure 7.

A high temperature environment test was run on this redesign model for an ambient temperature change from room to 700°C. The results are shown in Figure 8. The temperature at the end of 300 seconds of Surfaces 1, 2, 3, and 4 are 148°C, 140°C, 153°C, and 375°C respectively. The results were encouraging in this run because the critical Surfaces 1, 2, and 3 stayed as low as 105°C, 109°C, and 120°C at the end of 270 seconds. The mounting structure was further changed to have deeper notches and the surface area of contact with the base plate was further reduced as shown in Figure 9. The bread board model that was tested at NASA labs had such a design incorporated. The unit was examined after the test and the delicate electranics package had survived the high temperature environment and was also in working condition. This test confirmed that the heat insulation was more than adequate for the electranics package. The design itself was intended only to protect the package during this short duration and we can conclusively say that the housing design is the optimum design.

4.5 Mounting Design. The mounting design had to take into consideration the maximum vibration capabilities and also provide a minimum leakage path for the heat to flow up to the sensor package.

The obvious solution was to provide a minimum contact surface to the base as shown in Figure 10.

An experimental mock-up was resonance searche . The sensor and the voltage regulator are mounted on the base plate as shown in Figure 10. This structure has been resonance searched at 20 g's level and maximum displacement of 1/2 inch in the horizontal axis. No resonance was noticed below 2000 cps. This test was carried out with a mock-up model.

4.6 Housing Design. The prime objective in the housing design was to make it large enough to provide enough insulation and also to make the wall thickness heavy enough so that the walls will not burst due to the pressure build-up inside the housing.

Calculations were made for the wall thickness of the housing case as shown below.

The equation for the hoopstress = Pr/t, and longitudinal stress = $Pr/2t$

where P = Internal pressure = 55 psi (at 815°C)

r = Radius 1.75"

t = Thickness in inches.

The ultimate stress at 1500°F of 304 stainless steel = 5000 psi. The required radial thickness from the above calculation is 0.0192". We have chosen 0.062" wall thickness.

The end cover thickness calculated to be 0.01" and we have chosen 0.062" as a conservative estimate.

The breadboard model was built using a square configuration, Figure 11. The outside walls bulged when subjected to very high temperature. To conform with the theoretical work done on the cylinder, finalized engineering models were housed in a round can as shown in Figure 12.

5. PROBLEMS AND SOLUTIONS.

5.1. Design Problems and Difficulties. The low temperature performance of the leak sensor was a major problem which led to an extensive design change. The leak sensor and the associated piping could get down to a temperature of -155°C. At this low temperature the principle products of combustion (CO_2 and H_2O) freeze. Therefore, when the hot gas comes into the leak sensor, it would condense and freeze and no measurement would be possible. This is not a major problem with the external tubing because the tubing is expected to raise in temperature by 260°C in 5 seconds as the environment becomes hot immediately upon start-up. The sensor has much greater mass than the external tubing. It is placed inside a box packed with insulation to protect the electronics from the 815°C exposure and hence will not raise in temperature as fast as the surface of the box does. To overcome this problem, it was decided to use electrical heating to raise the temperature of internal tubing and gas pre-conditioning accessories to above 0°C. A design was arrived at giving the mass flow sensing device and gas pre-conditioning system a weight of 30 gms. This low weight design will make it possible to raise the temperature by 135°C with the allowable power and warm-up time. This design introduces another problem that, in the event that the temperature of the sensor is at 75°C to start with, then during the warm-up time the temperature of the system would go much higher than what the electronic component can take or if the warm-up time is much greater than 20 minutes, excessive temperature could result. As a solution to this problem an on-off temperature control device was used. This is described in the section on electronics.

6. <u>ELECTRONICS</u>. The design goals which were originally specified were as follows:

1. <u>Line Regulation</u>.

   $V_{in} = 28 \pm 3$ volts.

   $I_{load} = 36$ ma.

   $V_{out} = 20.000$ volts $\Delta V_{out} = 14$ mv.

   Regulation = 0.07%.

2. <u>Load Regulation</u>.

   $V_{in} = 28$ volts.

   $I_{load} = 36 \pm 4$ ma.

V_{out} = 20.000 volts ΔV_{out} = 1½ mv

Regulation = 0.07%

3. <u>RSS = 0.1%</u>.

4. <u>Drift = 1% or 200 mv</u>.

   T = -155°C to +75°C.

5. <u>Input to Output DC Isolation Also Required</u>.

To be considered throughout the design of this piece of equipment was the small package size. The small package size implies simplicity and small component size.

The original design consisted of a 1 KC oscillator and bridge for DC isolation and a single differentially operated, series regulation stage. The transistors were germanium because of the low temperature requirements and the positive leg of the supply was regulated.

At this point in the design, the biggest problem was selection of transistors which would operate at -155°C. Before this circuit could be finalized, the design criteria was changed to exclude the DC isolation. The regulation of this circuit did not meet the design criteria.

With the isolation requirement removed, a second stage of regulation was added and more work was done on component selection on the basis of low temperature operation. It was found that a GE 2N1183 would operate at -155°C. The gain of this transistor was greatly reduced at this temperature. The regulation and temperature drift of this circuit was greatly improved over that of the first circuit. Operation at -155°C was still not satisfactory.

All the components would not function over the entire ambient temperature range of -155 to +75°C a heater circuit was added to the electronics assembly. The transistors and sensors were to be heated from -155°C to 0°C. Heating of the transistors required that they be packaged in the same plane.

This change necessitated a change in transistors. The transistors were changed to a silicon type to withstand the high operating temperature requirements. The use of silicon transistors led to the regulation of the negative leg of the supply. Output voltage drift was to be less than 1% with an ambient temperature rise of from 0°C to +125°C.

Our problem in the design of this circuit was poor load regulation. One approach to improve the load regulation was to increase the closed loop gain of the system by adding the additional stage of amplification and using a Darlington pair for the series regulator. This approach did not help appreciably. The problem was solved by adding a small resistance in series with the regulated leg of the supply. Either positive or negative regulation could be achieved by varying this resistance. The cross-over point is selected for operation. This resistance is adjusted when the electronics package is mated with the sensor.

To this circuit, a heater control circuit was added. A bimetalic temperature controller was intended, but to ensure insensitivity to vibration, a solid state switch controlled by a thermistor was used. Parts to be used were suggested by NASA. A type 2N1714 transistor was used instead of a type 2N1718 because of case size. This series of transistors was found to operate at -160°C but with a loss in gain of about 75%.

After the bread board model was submitted for approval the specifications were changed to include input to output DC isolation. This was accomplished by adding a 2KC oscillator and full wave rectifier to the existing circuit.

This change necessitated some changes in the regulator component values and complete redesign of the package and printed circuit boards.

A problem area in packaging the supply was selecting a suitable potting material. The material selected had to meet the following requirements. (a) It had to be relatively light weight. (b) It had to be a poor heat conductor because of limitations and available heater power. (c) It had to withstand, without deterioration, the extreme temperature variations imposed on the equipment. (d) It must have a negligible coefficient of thermal expansion over the entire operating range, (-155°C to +125°C). (e) It must not expand or contract appreciably when being cured.

A suitable combination a found to be 3M glass beads and Dow Corning Sylgard 182 potting compound. Vacuum potting was used to combine the two.

The final circuit diagram is Figure 13 (REC Dwg 530-15).

This circuit has the following characteristics:

<u>Load Regulation</u>:

V_{in} = 28 volts

I_L = 36 ± 5 ma

V_{out} = 20.000 volts $\pm$ 1 mv

Regulation = 0.01%

Line Regulation:

V_{in} = 28 $\pm$ 4 volts

I_L = 36 ma

V_{out} = 20.000 volts $\pm$ 1 mv

Regulation = 0.01%

RSS = 0.014%

DRIFT: The thermal drift of the output voltage over the temperature range of 0°C to +125°C is less than 0.7%.

To provide an operational check point for calibration checks the necessary points on the bridge will be brought out so that when a calibrated resistor is connected across Pin C and D, the leak sensor will have a positive output.

7. VERIFICATION TESTS. The following tests were performed on the completed breadboard unit to verify the design.

7.1. Calibration.

7.1.1. Room Temperature. The calibration method is the collection of a known quantity of gas that is flowing through the sensor and the time required measured using a stopwatch, using the set up shown in Figure 14. Using this data we obtain the cc/min flow rate of the gas. The barometric pressure and ambient temperature are measured and using this value the cc/min is converted into Std cc/min. The conversion factor for std cc/min air to the std cc/min of "hot gas" (referring to the specified mixture of combustion products) will be

$$1 \text{ Std cc/min air} = \frac{(C_p\ \rho_{\text{std conditions}})\ \text{Hot Gas}}{(C_p\ \rho_{\text{std conditions}})\ \text{air}}\ (\text{Std cc/min of hot gas})$$

$$1 \text{ Std cc/min air} = 1.0803 \text{ Std cc/min Hot Gas}$$

The data obtained by calibrating the sensor at 25°C ambient and gas temperature of 25°C is tabulated in Table I and a plot is shown in Fig.16.

7.1.2 Hot Calibration. The sensor was calibrated with the ambient temperature at 101°C and gas temperature at 25°C. The data obtained is presented in Table II and a plot is shown in Figure 16.

7.2. Time Constant. The time constant test set is as shown in Figure 15. Using this set-up we can change the flow rate from one value to another. Valve 1 is cracked open so that we get a particuler flow rate through the sensor. The flow velocity at the exit of the Valve 1 is sonic and hence any further lowering of the downstream pressure will not change the mass flow rate. Then Valve 2 is cracked open so that the output of the transducer drops by a predetermined amount. Now by suddenly opening or closing the inlet of Valve 2, a step change in flow can be simulated. The volume between the leak sensor and the valve is kept to a minimum so that the pneumatic time constant would be very fast compared to that of the leak sensor. Using this method the time constant was measured for various step changes. The data obtained is shown in Table III.

7.3. Vibration. The sensor was vibrated at zero flow at a vibration level of 10 g's sine wave and 0.5 inches maximum amplitude through a frequency range 5-2000 cps, 3 minutes up and 3 minutes down in the horizontal axis and vertical axis. An error of less than 2% of full scale resulted between 8 and 200 cps and the unit was stable through the rest of the frequency band.

7.4 Attitude Sensitivity. The sensor was checked for attitude sensitivity in all three axes. The sensor was placed in each axis and checked for change in output. No attitude sensitivity was noted.

7.5 Thermostat Control Test. The sensor was taken down to the temperature of dry ice and then the poer was switched on. The current drawn was 151 ma and in a period of 15 minutes the current came down to a value of 53 ma. This indicated that the control circuit was in ope ation. This test was performed to test starting capability of the electronics package at dry ice temperature. In actual use this power would be turned on when sensor is at ambient conditions and then the temperature would be cycling cold and going as far low as -155°C but the heater will not allow the temperature of the package to get down below 0°C.

7.6 Pressure Drop. Using a mercury manometer, a pressure drop of 3.92 psi was measured across the sensor with a flow rate of 1000 std cc/min of air.

7.7 One hot gas unit was calibrated with hot air at 400°, 500°C, 700°C and 925°C and the data obtained is plotted in Figure 17 of this report.

8. NEW TECHNOLOGY. A report (REC Report 2643) of New Technology is given in Appendix A.

9. FINALIZED SPECIFICATIONS. The finalized specifications are shown in Figure 16, REC Specification Drawing 124D.

REFERENCES

1. E.R.G. Eckert and R. M. Drake, Jr. "Heat and Mass Transfer" McGraw-Hill Book Co., Inc. New York, 1959.

2. R. L. Daugherty A.B., M.E. and A.C. Ingersoll, PhD. "Fluid Mechanics with Engineering Applications", McGraw-Hill Book Co., Inc. New York, 1959.

3. Max Jakob "Heat Transfer" Volume 1, John Wiley and Sons, Inc. New York.

4. Paul J. Schneider, "Temperature Response Charts" John Wiley and Sons, Inc., New York, 1963.

5. Lionel S. Marks and Theodore Baumeister "Mechanical Engineers Handbook", McGraw-Hill Book Company, Inc.

TABLE I

Room Temperature Calibration
Model 124D, S/N HG-6

Mass Flow Rate Std cc/min Air	Output Millivolt
929.9	10.44
859.7	10.22
765.8	9.94
706.1	9.72
608.3	9.31
549.5	9.03
474.01	8.62
330.1	7.6
262.3	6.95
139.5	4.81
63.9	2.33
0	.61

TABLE II

High Temperature Calibration
Model 124D, S/N HG-6

Mass Flow Rate Std cc/min Air	Output Millivolts
814.3	9.8
745.5	9.55
700.6	9.38
635.7	9.11
580.3	8.84
532.97	8.6
446.9	8.13
311.6	7.06
240.4	6.22
164.2	4.88
69.04	2.15
0	.51

TABLE III

Time Constant
Model 124D, S/N HG-6

Step in Flow Std cc/min Air		Time Constant Seconds
from	to	
35	150	1.7
75	250	1.15
190	1000	0.75
35	1000	0.7

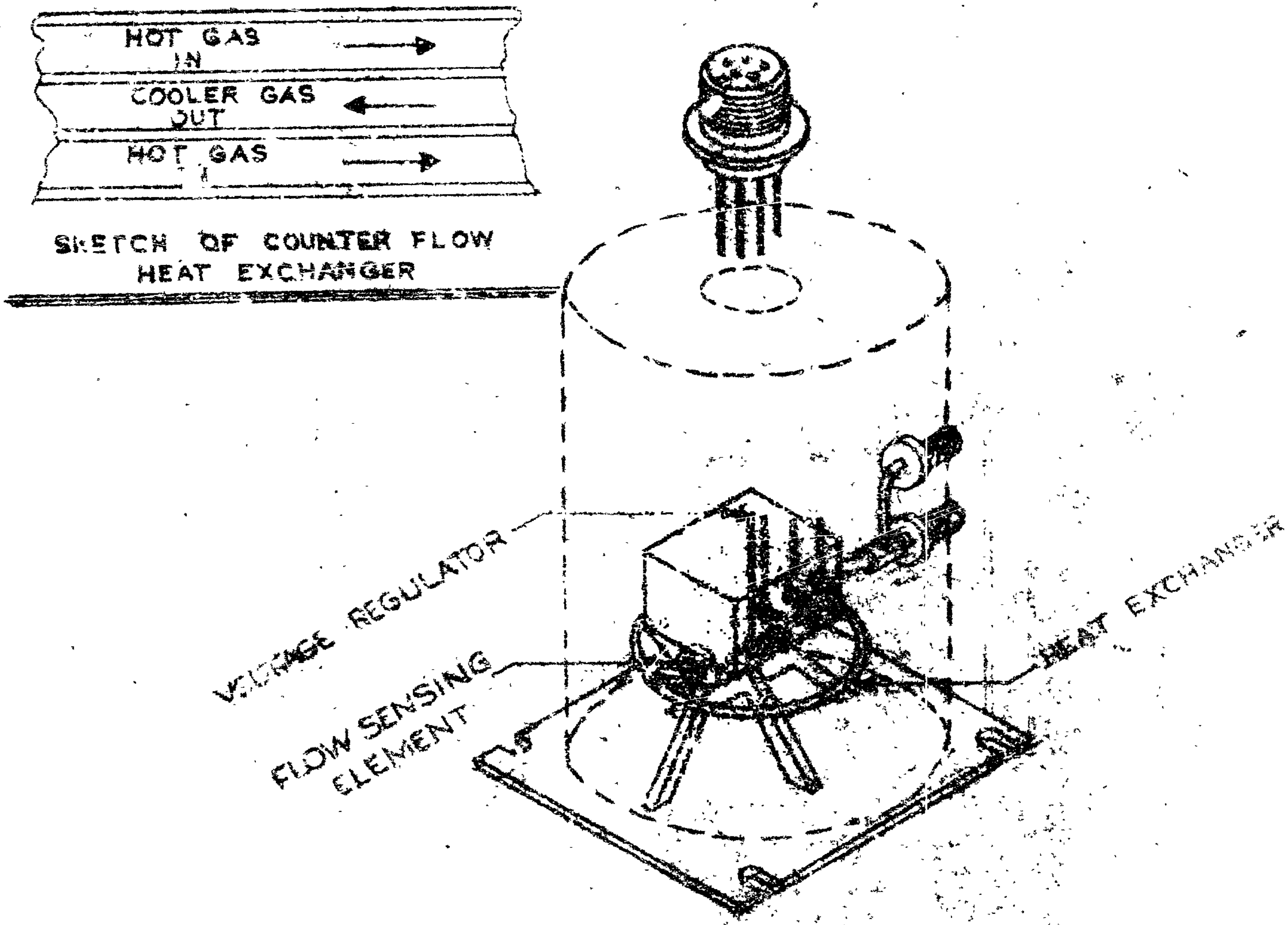


FIG. 1. INTERIOR CONSTRUCTION OF HOT GAS LEAK SENSOR

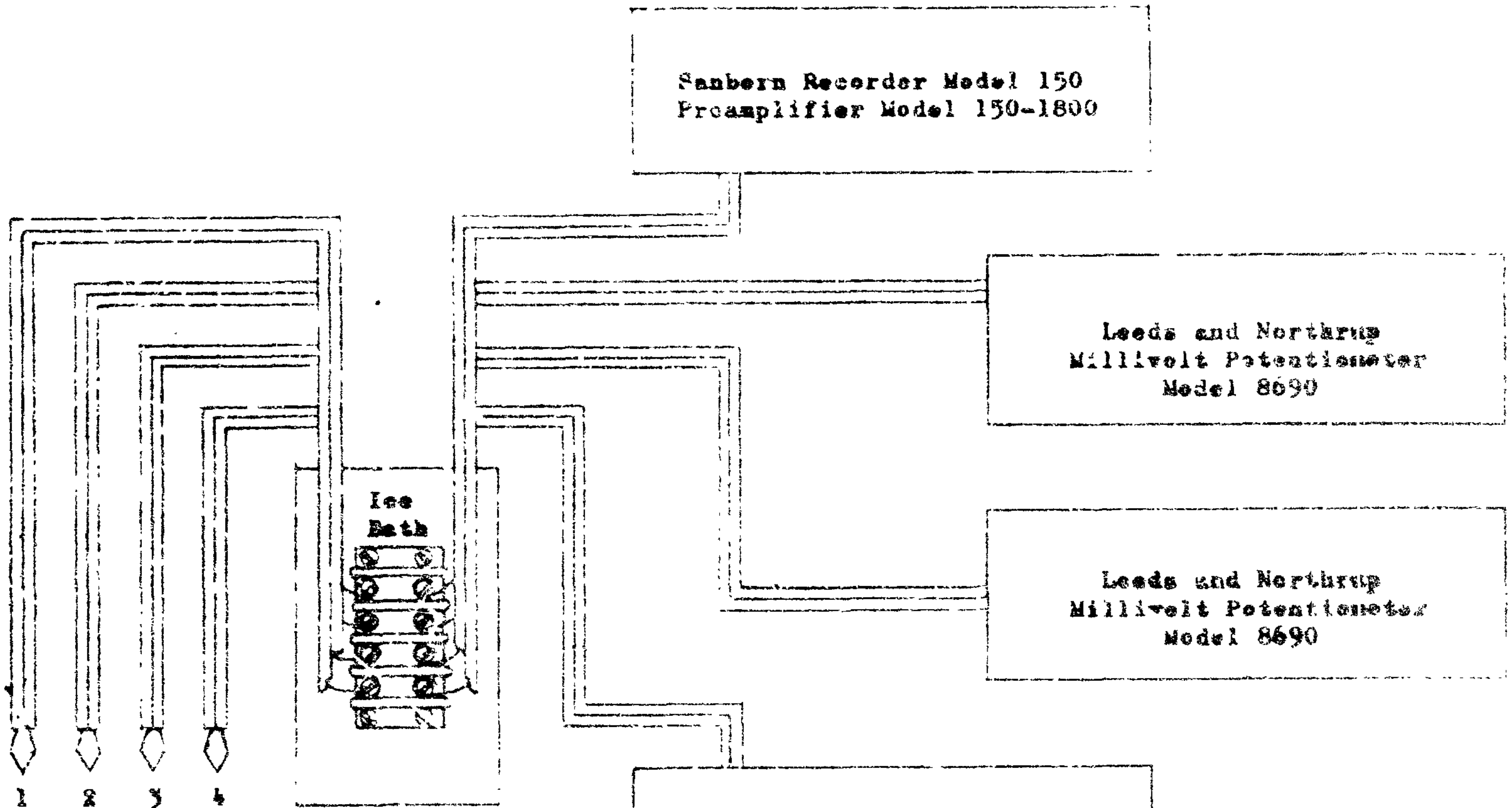
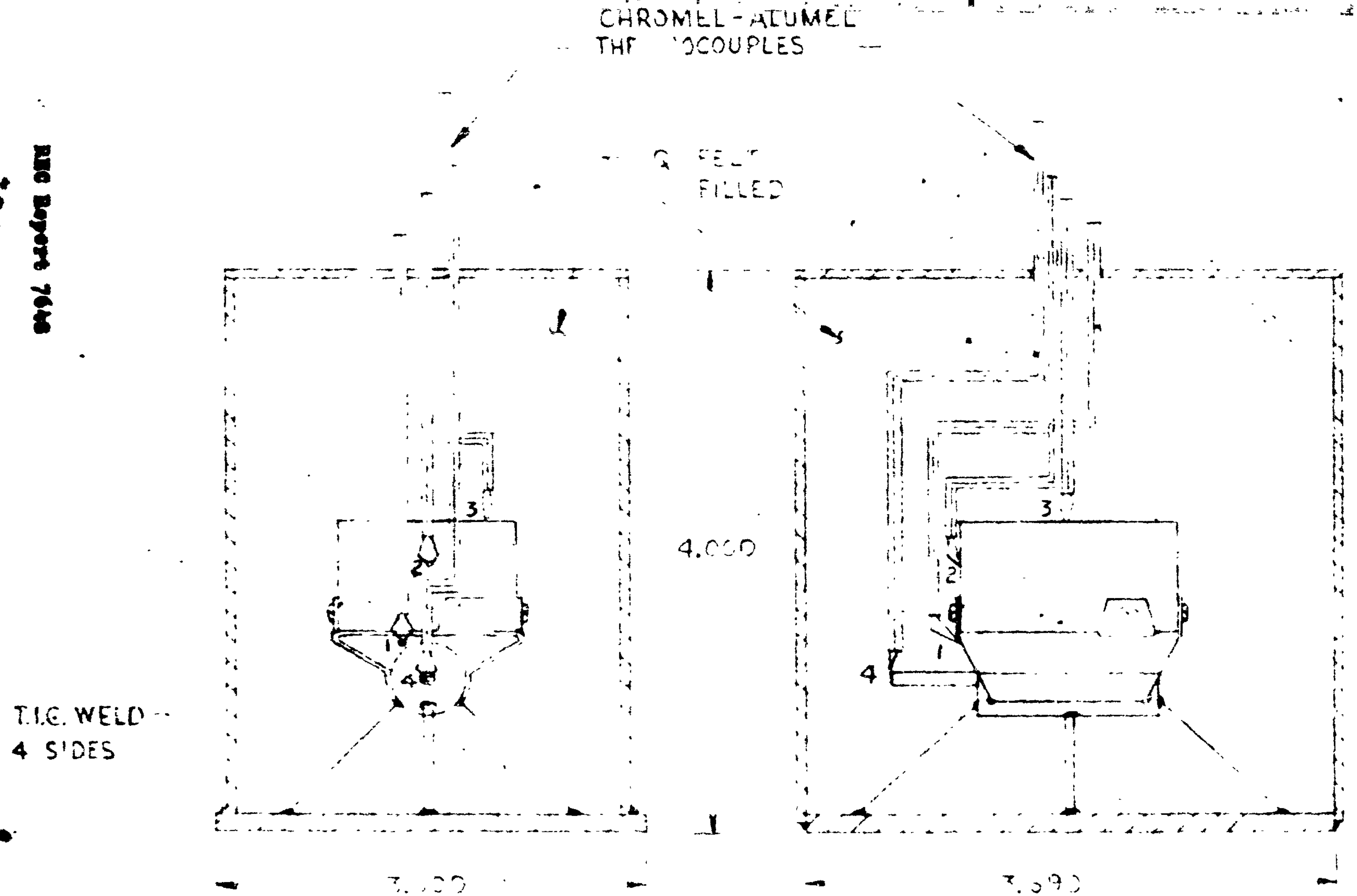


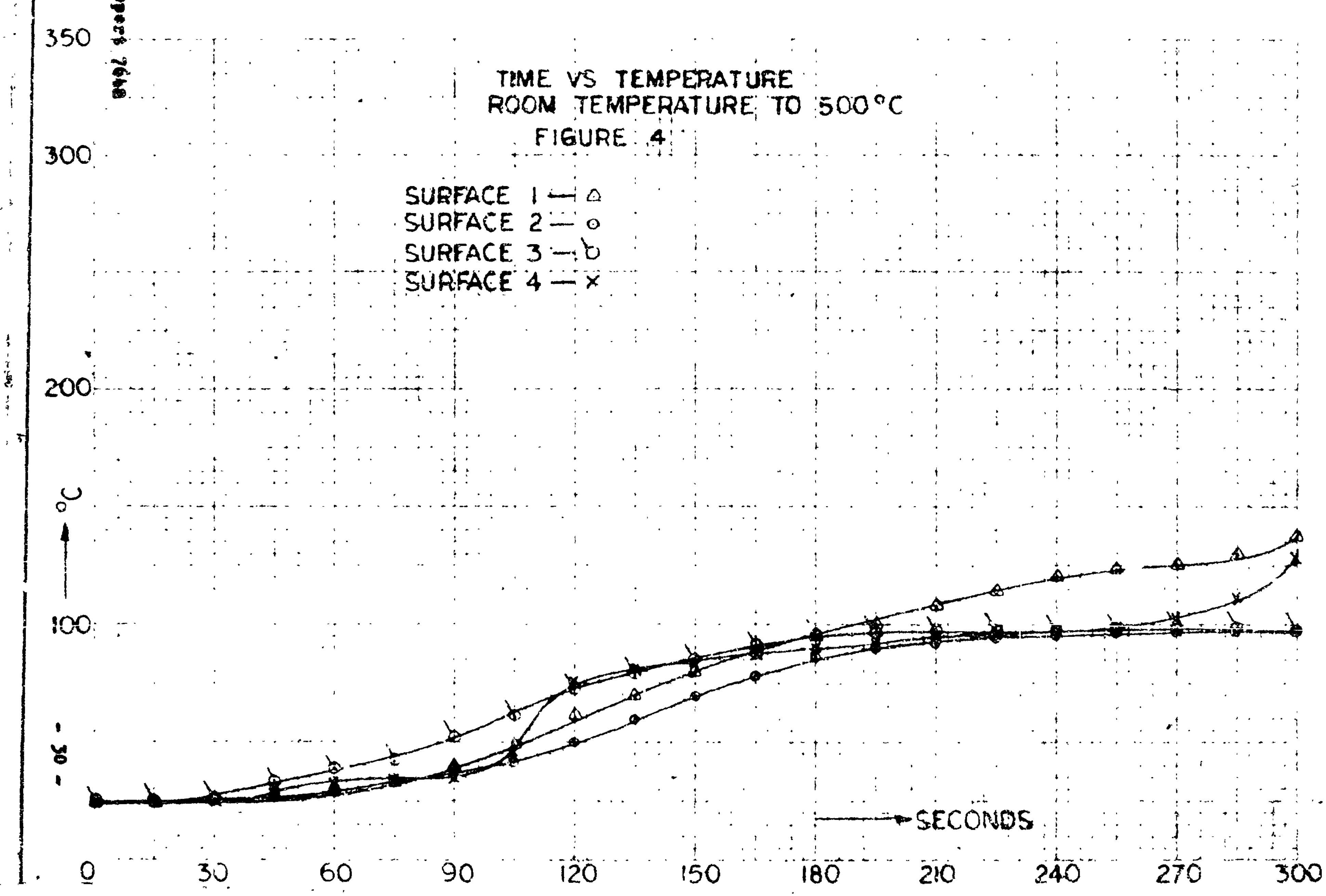
FIGURE 3

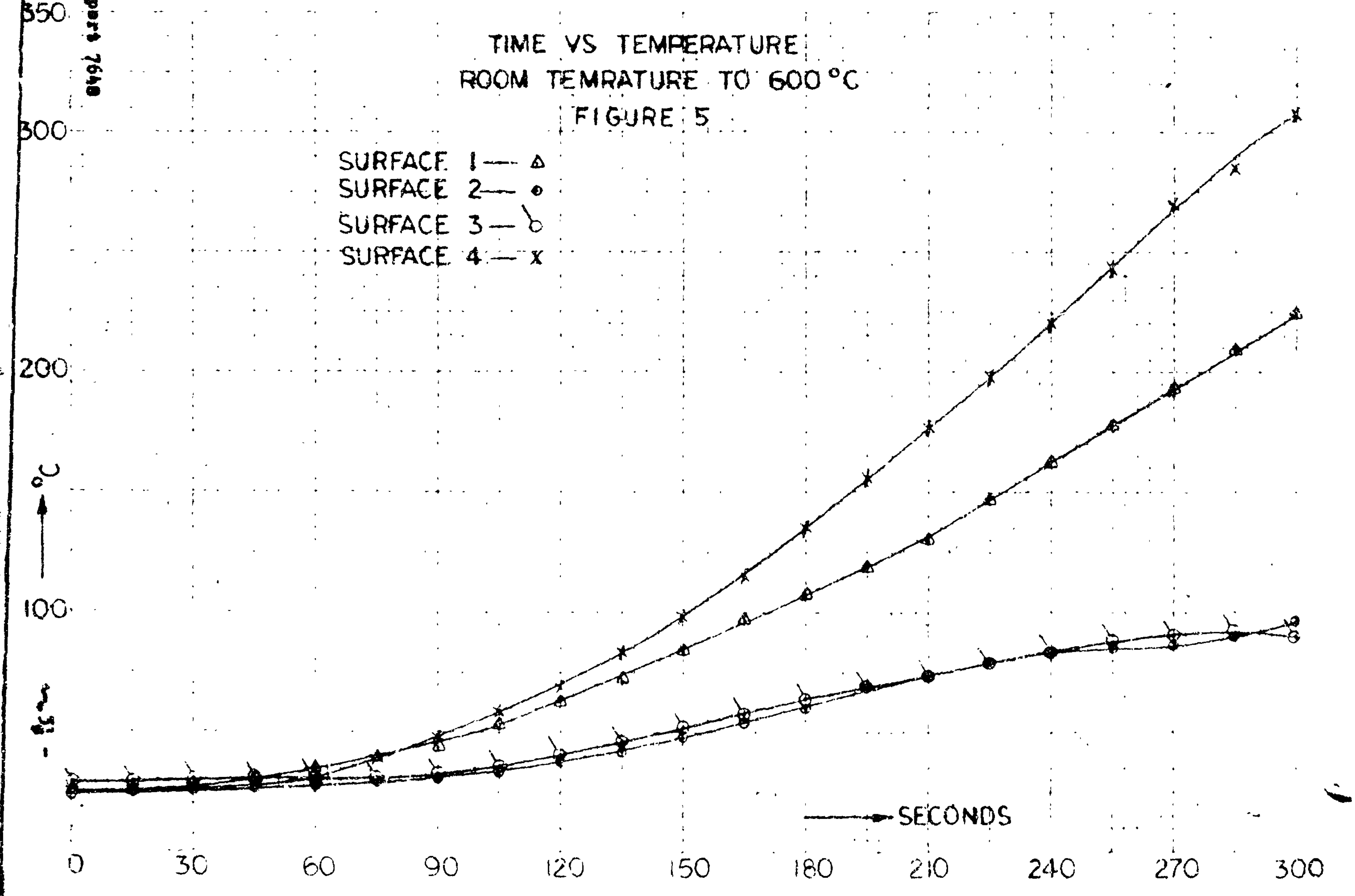
TEMPERATURE MONITORING SET UP
FOR HIGH TEMPERATURE ENVIRONMENT TEST



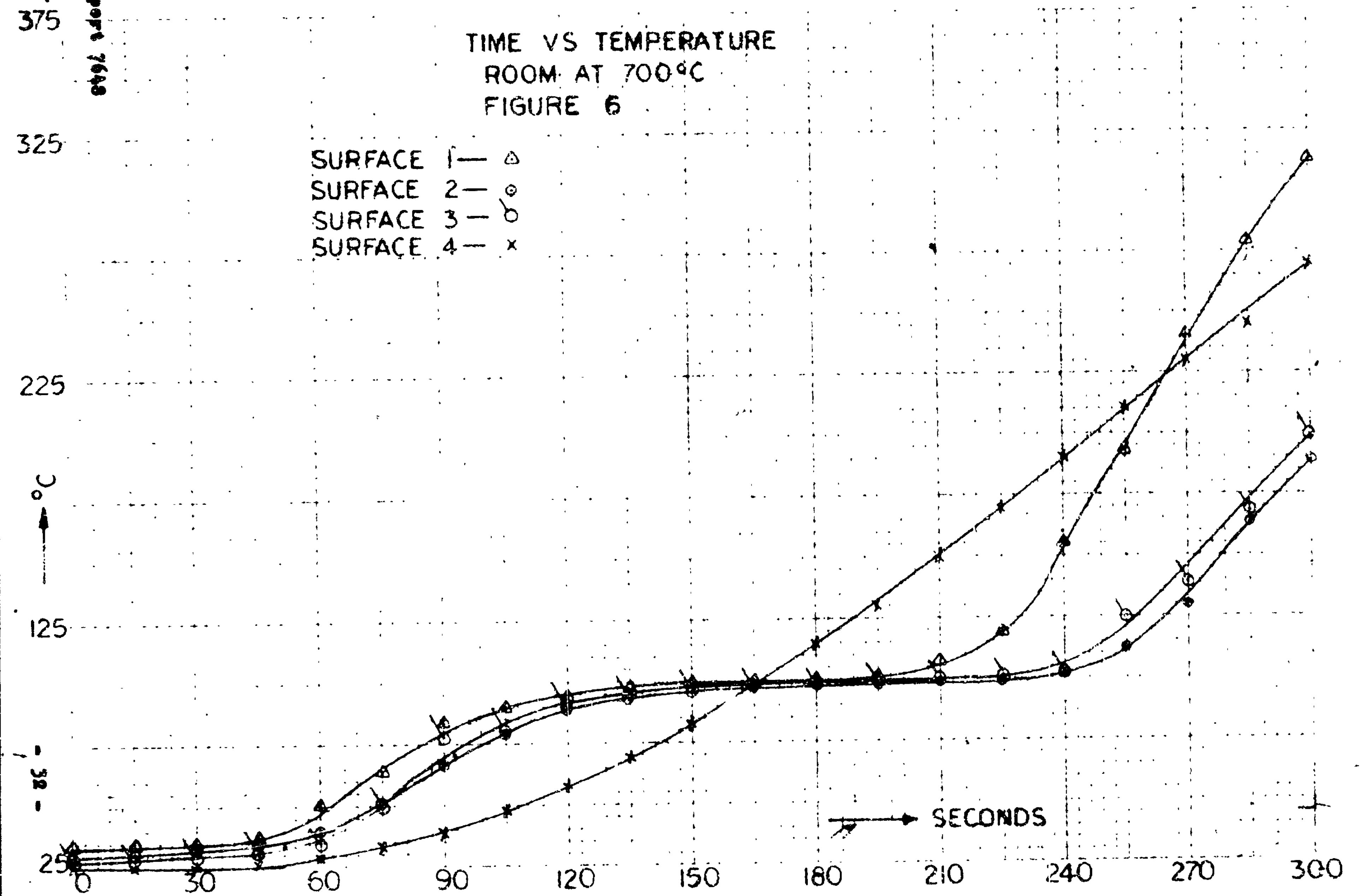
HIGH TEMPERATURE SET UP

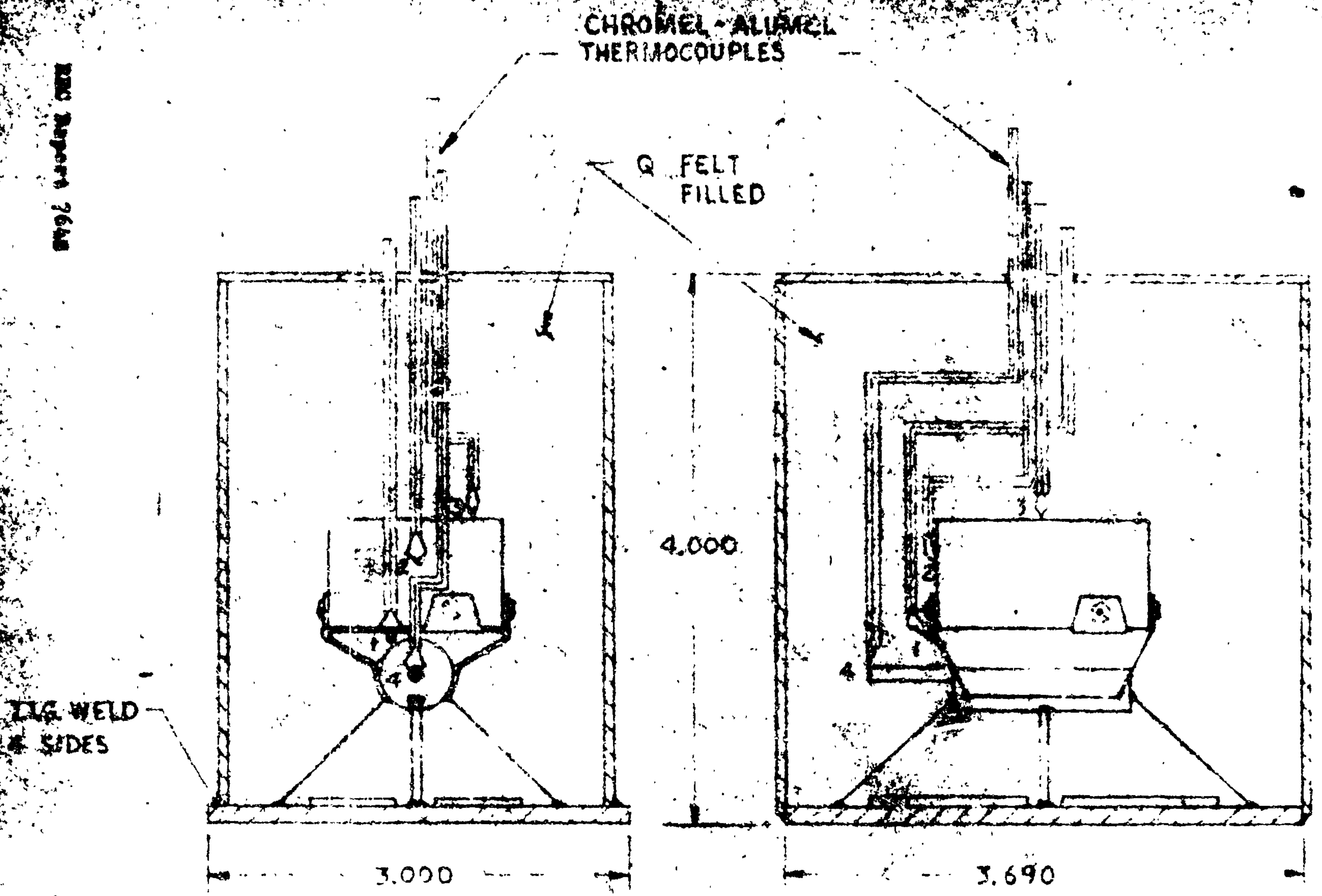
FIGURE 2


TIME VS TEMPERATURE
ROOM TEMPERATURE TO 500°C
FIGURE 4
SURFACE 1 — △
SURFACE 2 — ○
SURFACE 3 — ϑ
SURFACE 4 — ×
°C
350
300
200
100
30
SECONDS
0
30
60
90
120
150
180
210
240
270
300



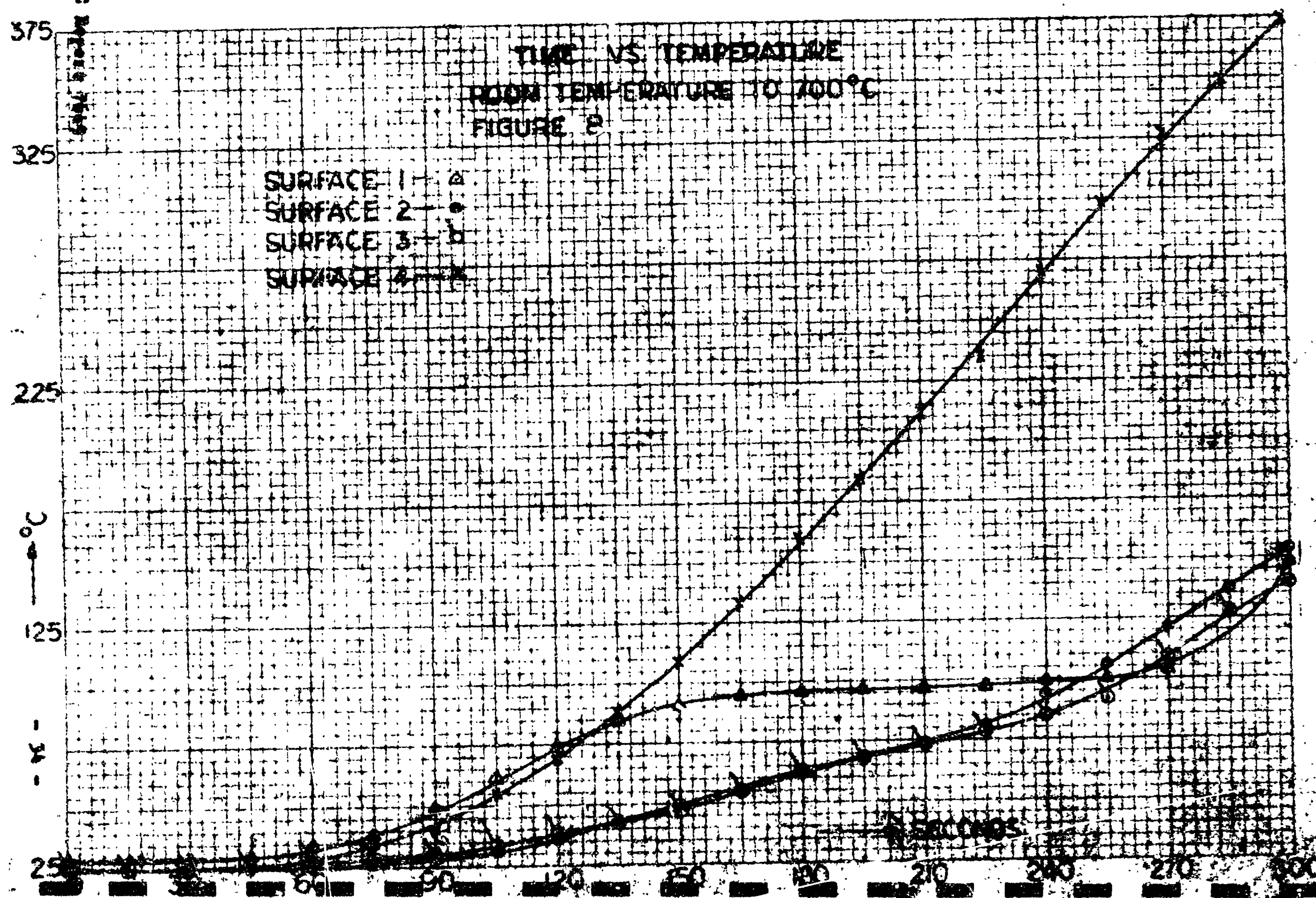
TIME VS TEMPERATURE
ROOM TEMRATURE TO 600 °C
FIGURE 5


TIME VS TEMPERATURE
ROOM AT 700°C
FIGURE 6
SURFACE 1 — △
SURFACE 2 — ⊙
SURFACE 3 — ○
SURFACE 4 — ×
°C
375
325
225
125
25
SECONDS
0
30
60
90
120
150
180
210
240
270
300

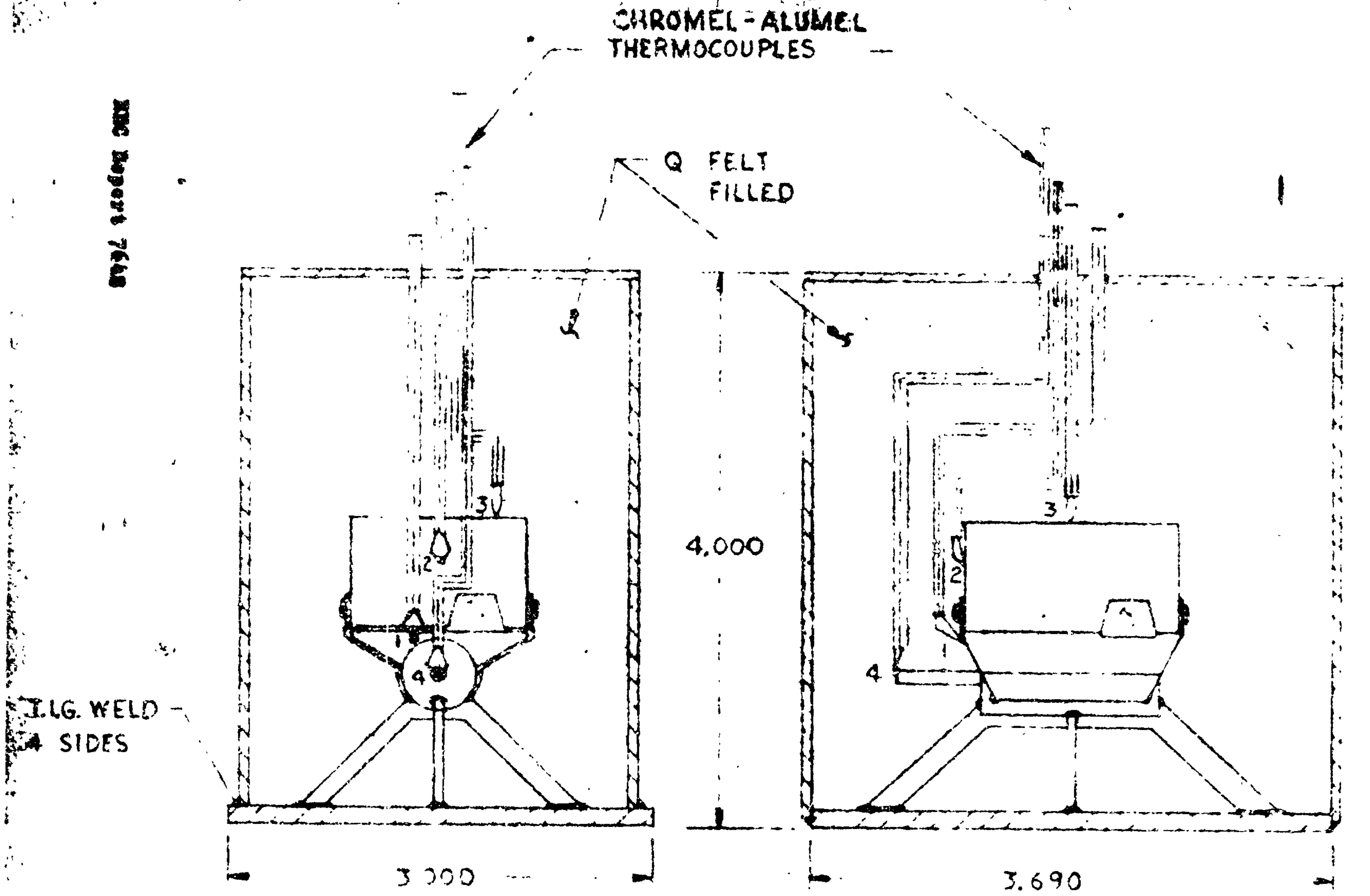


HIGH TEMPERATURE SET UP

FIGURE 7

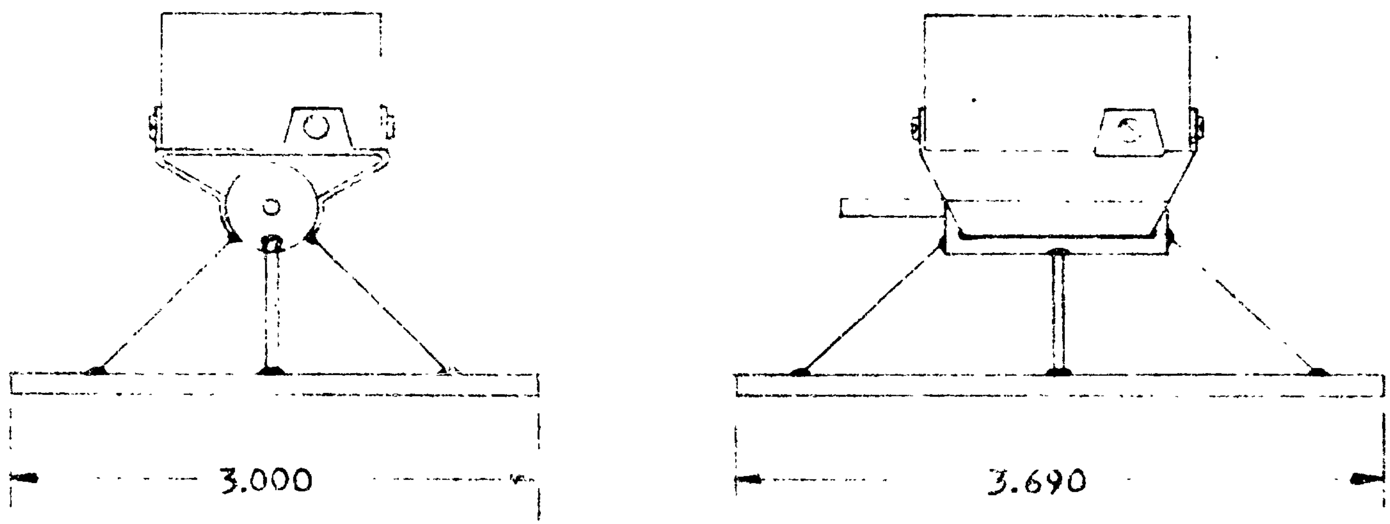


TIME VS TEMPERATURE
ROOM TEMPERATURE TO 700°C
FIGURE 2
SURFACE 1 — △
SURFACE 2 — ●
SURFACE 3 — ◻
SURFACE 4 — ×
375
325
225
125
25
°C
SECONDS
60
90
120
150
180
210
240
270
300



HIGH TEMPERATURE SET UP

FIGURE 9



MOUNTING ASSEMBLY

FIGURE 10

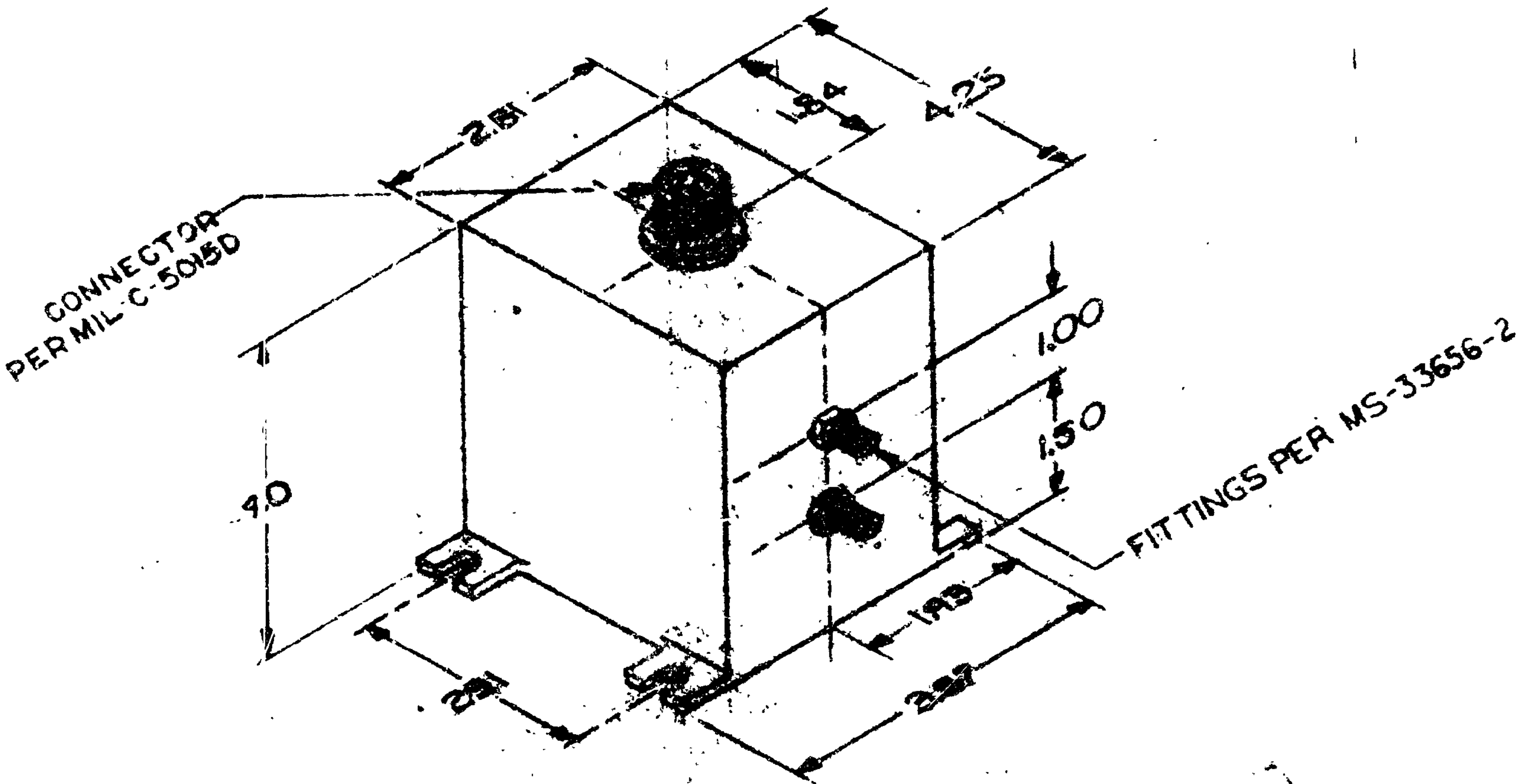


FIGURE ELCPE FOR BREAD BOARD UNIT

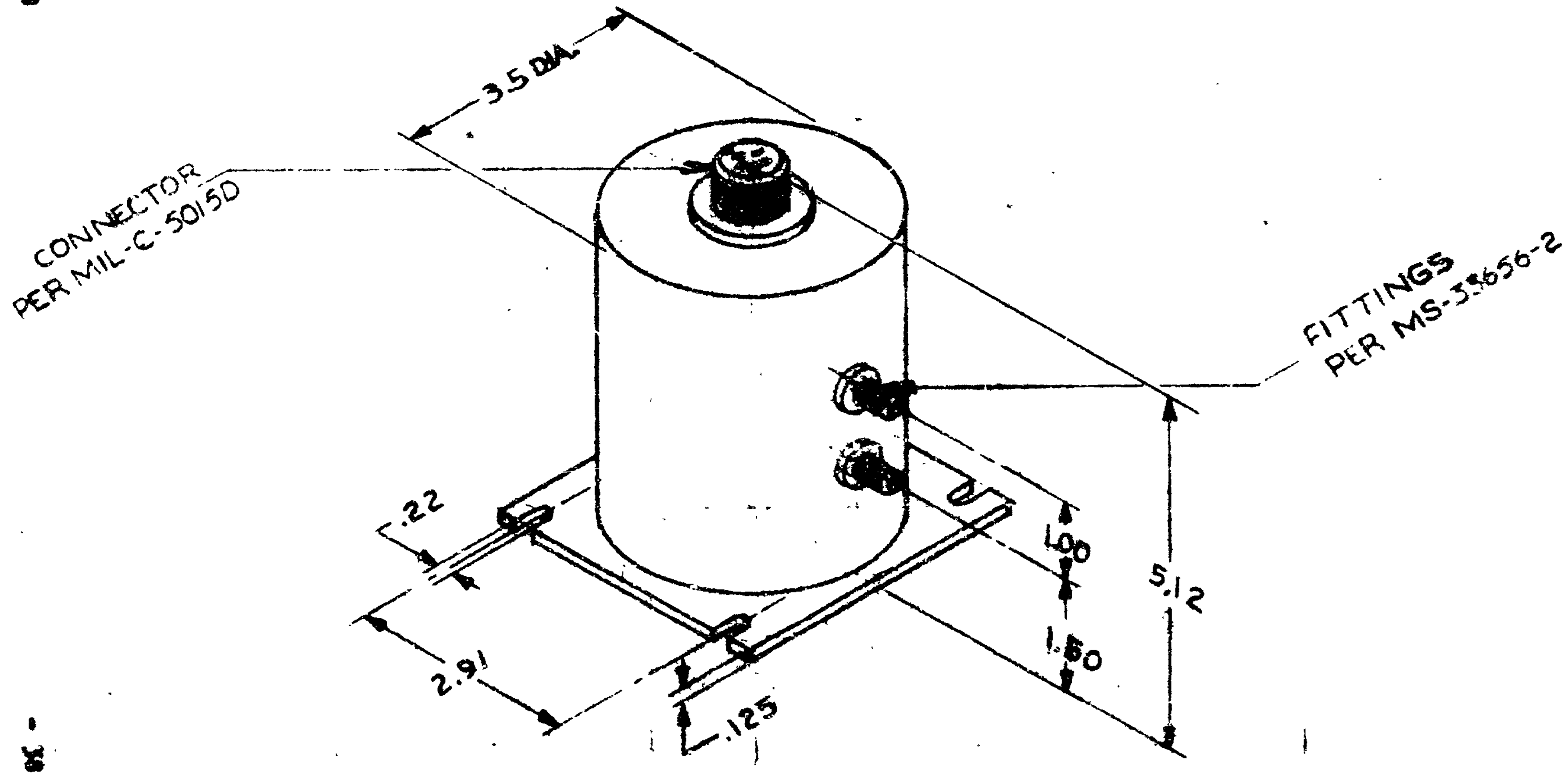
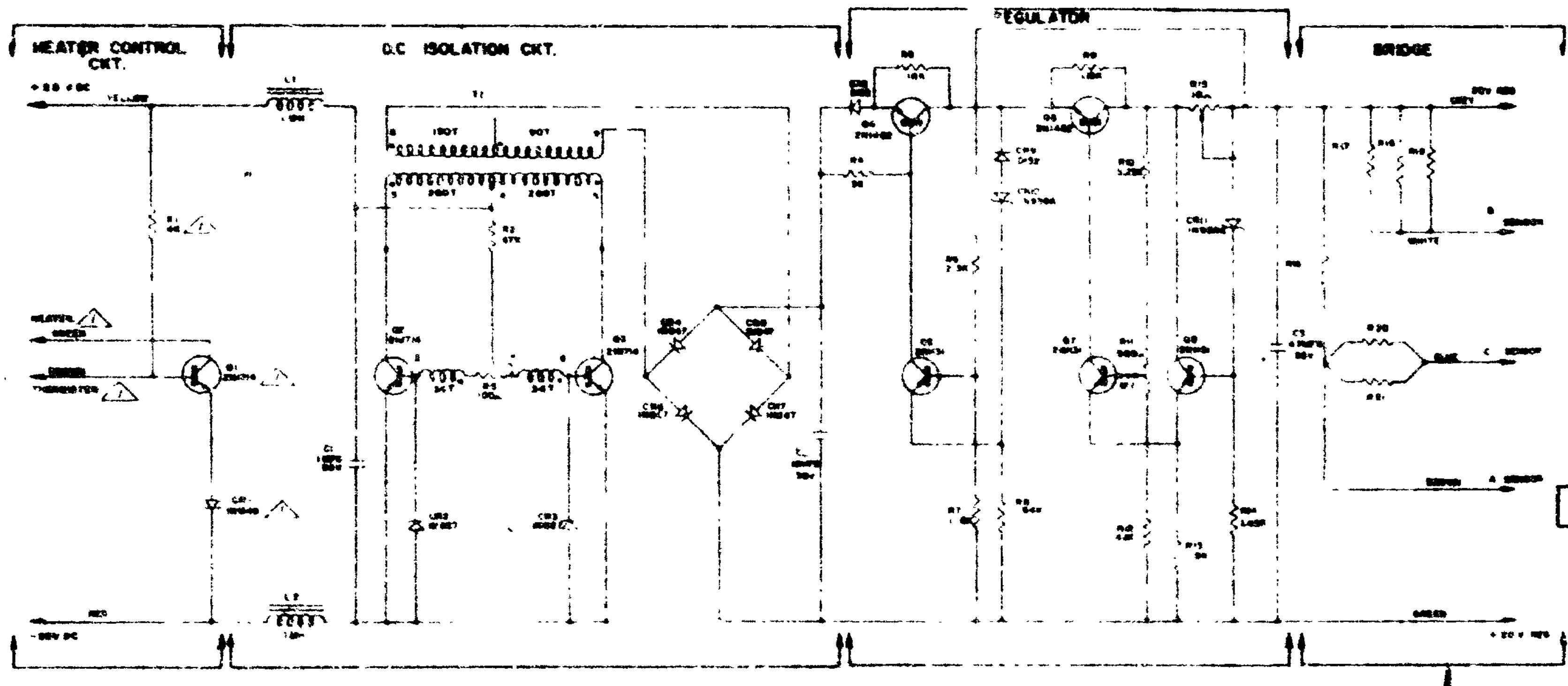


FIG. 12: MODIFIED ENVELOPE

TABULATION

DWG NO	DESCRIPTION
530-15-1	AS SHOWN
530-15-2	OMIT ITEMS

REVISIONS



530-15

LIST OF MATERIAL

POWER SUPPLY AND BRIDGE

530-15

NEXT ASSY 530-9

MODEL 530C

SEE TAB

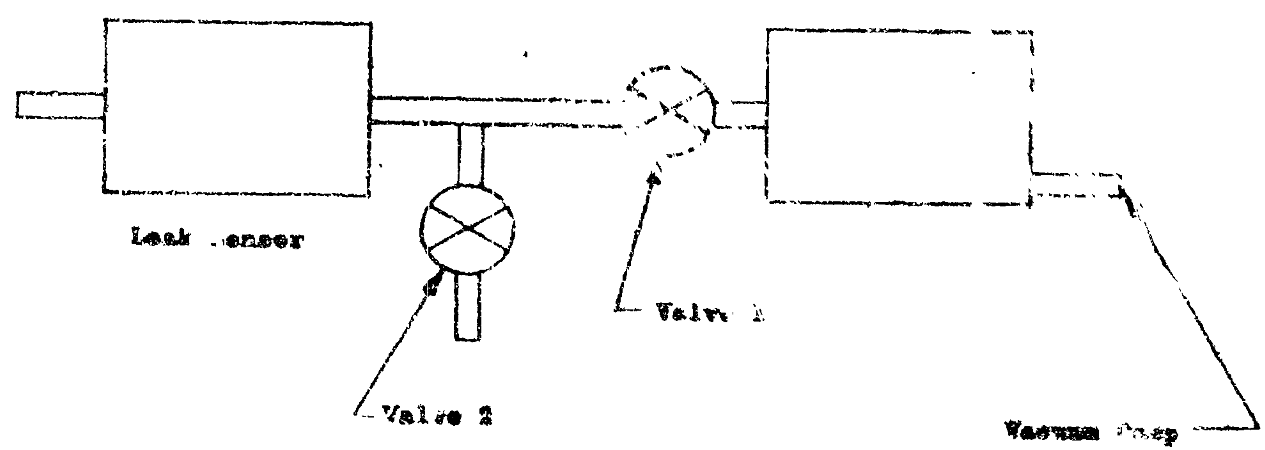


FIGURE 15

TIME CONSTANT TEST RIG

NRL Report 7648

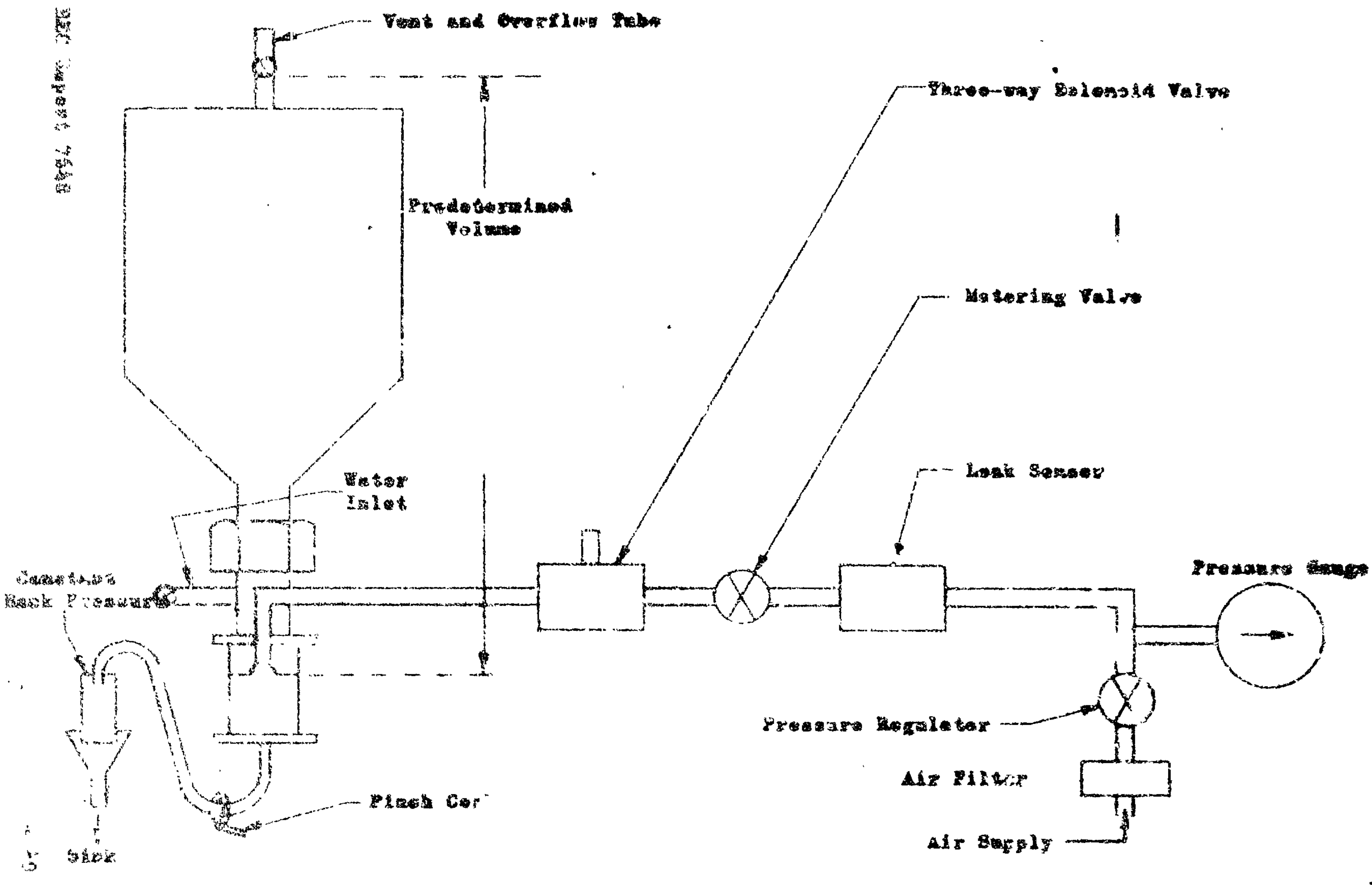


FIGURE 14

CALIBRATION SET UP FOR LEAK SENSORS

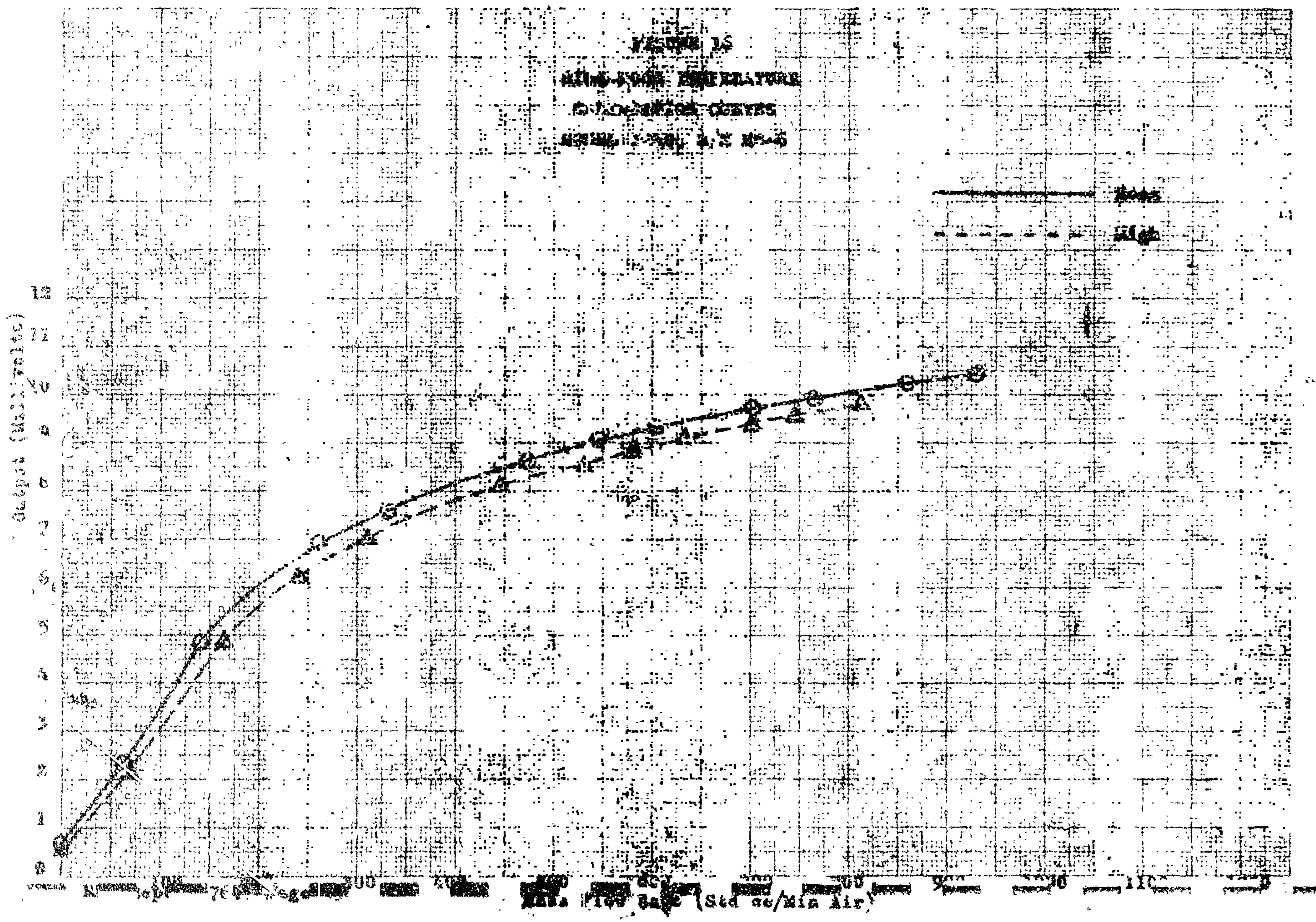


FIGURE 15
Room
High
Output (Millivolts)
Mass Flow Rate (Std cc/Min Air)

SPECIFICATIONS

1. SCOPE. The [illegible] sensor [illegible] can be modified to measure flow rates over any full scale range from 0 to [illegible] up to 0 to 33,000 or more standard cc/min. It uses a flow sensing element made of stainless steel tubing. These sensors are suitable for use in most hydrocarbons, gaseous or liquid air, oxygen, nitrogen, hydrogen, helium or hot exhaust gases. Various full scale ranges are obtained by shunting part of the flow [illegible] by changing the sensing element geometry. In the following, [illegible] flow of the products of combustion of O_2 with HF [illegible] and temperature of the hot gas of [illegible] to 925°C). [illegible]

2. [illegible] PERFORMANCE CHARACTERISTICS.

2.1 [illegible]. [illegible] a particular sensor shall meet the requirements of this specification at any flow [illegible] range 0 to 200 standard cc/min and 0 to 1000 standard cc/min of air.

2.2 Flow Rate - Output Relationship. [illegible] sensor shall meet the flow rate - output relationship shown in Table I and [illegible] within the interchangeability [illegible] indicated.

2.3 [illegible]. Each sensor shall be calibrated through 0 standard cc/min, 50 standard cc/min, 100 standard cc/min, [illegible] standard cc/min, [illegible] standard cc/min, and 1000 standard cc/min [illegible] accurate within [illegible] of full scale, using air as the fluid medium.

2.4 Repeatability. Readings taken [illegible] under the same conditions shall repeat within [illegible] full scale reading.

2.5 Insulation Resistance. At room temperature, with dry external surfaces, the insulation resistance between the receptacle pins and the sensor shall exceed 50 megohms measured at 100 volts DC.

2.6 Time Constant. When quickly changing the flow rate from 10 standard cc/min to 1000 standard cc/min, [illegible] percent of the total response of the sensor [illegible] in less than 0.2 seconds (air).

2.7 Pressure. Each sensor shall not be damaged or leak when subjected to 100 psig in flow path.

2.8 Vibration. The sensor shall [illegible] properly when subjected to (a) random noise with a band width of 20 [illegible] and (b) random noise motion of [illegible] g's [illegible] for 5 seconds and [illegible] g's [illegible] for a period of 120 seconds.

2.9 Shock. The sensor [illegible] by a impact shock of 100 g's for 10 milliseconds triangular wave or 100 g's for 8 milliseconds sine wave, or [illegible] g's for [illegible] milliseconds square wave.

2.10 Current. [illegible] current of 20 milliamperes [illegible] shall not damage the sensor.

2.11 Accuracy. The sensor shall perform with [illegible] of full scale accuracy over a temperature range of [illegible] to 75°C and [illegible] for [illegible] minutes and pressure of 760 mm Hg to 10^{-5} mm Hg.

2.12 Materials of Construction. Material in contact with the fluid is 304 stainless steel and silver solder.

2.13 Identification. The following minimum information shall be electroetched on the head of the sensor:

Hot Gas [illegible] Sensor
Serial No. ________
Model No. [illegible]
Rosemount Engineering Company

2.14 Power. The sensor shall operate from [illegible] VDC [illegible] supply and shall not dissipate more than [illegible] watts

2.15 Weight. The weight of the transducer shall not exceed 2 pounds [illegible] ounces.

2.16 [illegible]. The sensor shall not be [illegible] to changes in attitude.

2.17 Back Pressure. The sensor shall not [illegible] a back pressure in excess of [illegible] psi.

2.18 Insulation. Between [illegible] and output pins, the isolation resistance shall be greater than 100 megohms at 50 volts DC.

2.19 Operational Check. When a resistor is connected between pins C and D a positive going signal will occur at the output pins.

3. INDIVIDUAL TESTS. Each sensor shall be [illegible] for good workmanship, conformance to this drawing, and shall undergo the test defined or implied by paragraphs 2.3, 2.5 and 2.7 of this specification. The results of these tests shall be recorded on a [illegible] which two copies shall be packed for shipment with the sensor.

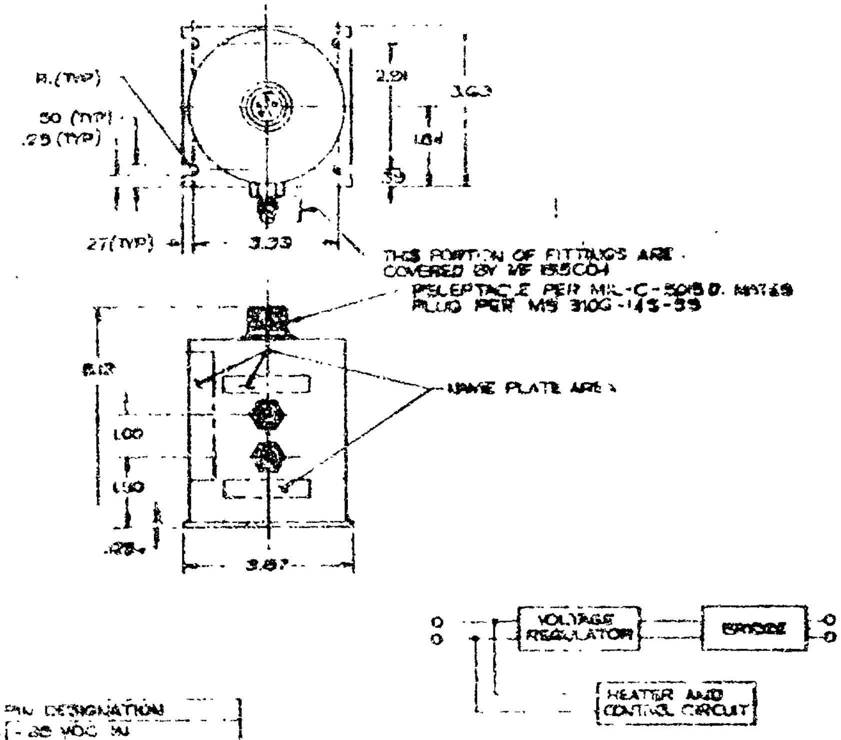
Table I

Flow std cc/min Air	Output (millivolts)	Interchangeability* (millivolts)
0	[illegible]	±0.11
50	[illegible]	
100	[illegible]	
[illegible]	[illegible]	
200	[illegible]	±0.[illegible]

Table II

Flow std cc/min - Air	Output (Millivolts)	Interchangeability* (Millivolts)
0	0	±0.11
250	5.1	
[illegible]	7.15	
[illegible]	8.[illegible]	
750	9.19	
1000	10.0	±0.55

*Interchangeability is [illegible] deviations from the end points of the curve when operated at 25°C with [illegible] volts DC supplied.



PIN	DESIGNATION
A	- 28 VDC IN
B	+ 28 VDC IN
C	- SIGNAL OUT
D	OPERATIONAL CHECK
E	+ SIGNAL OUT

ROSEMOUNT ENGINEERING COMPANY
MINNEAPOLIS, MINN.

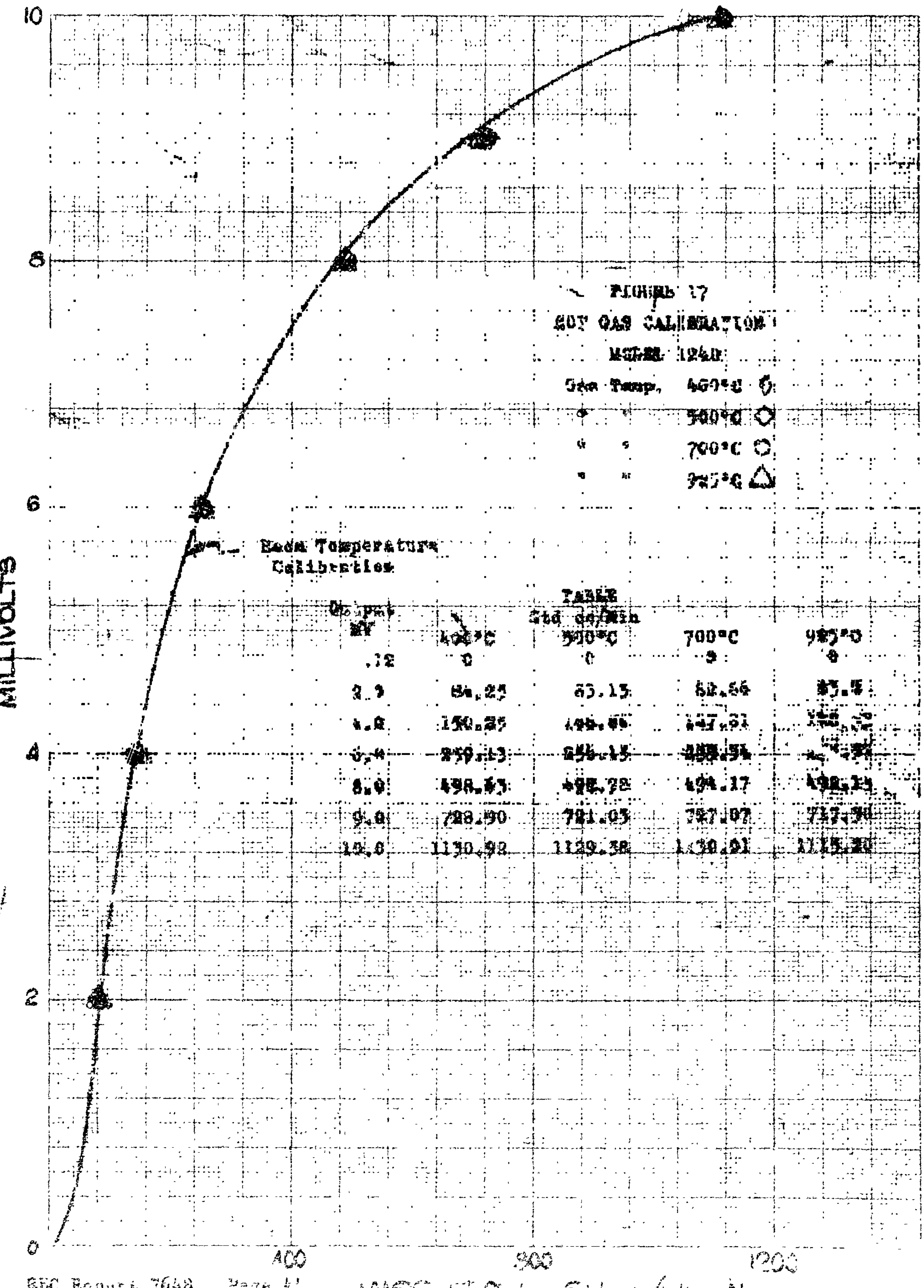
SPECIFICATION DRAWING
THERMAL MASS FLOW SENSOR

SIZE C — DRAWING NO. 124 D — REV H

Code ident no. 04974 — Scale 1/2

Drawn: [illegible] 2-4-64
Checked: R. [illegible] 2-4-64
Appd: E. [illegible] 2-4-64

124 D — H
REVISIONS: H — [illegible]



TABLE

Output MV	Std cc/min 460°C	500°C	700°C	985°C
.12	0	0	0	0
2.0	84.25	83.13	82.66	85.5
4.0	150.25	[illegible]	[illegible]	[illegible]
6.0	250.13	[illegible]	[illegible]	[illegible]
8.0	498.63	495.72	494.17	492.15
9.0	728.90	721.03	727.07	717.90
10.0	1130.92	1129.38	1130.01	1115.20

ROSEMOUNT ENGINEERING COMPANY
4900 West 78th Street
MINNEAPOLIS 24 MINNESOTA
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APPENDIX "A"

NEW TECHNOLOGY REPORT

NASA Contract NAS8-5451

DEVELOPMENT OF SENSOR TO MEASURE HOT GAS LEAKS FROM FLANGES AND SEALS IN PLUMBING OF SATURN VEHICLES

REC Report 2643

Date: 4 February 1964

Prepared for George C. Marshall Space Flight Center

(Donich)

NEW TECHNOLOGY REPORT

NASA Contract NAS8-5651

DEVELOPMENT OF SENSOR TO MEASURE
HOT GAS LEAKS FROM FLANGES AND SEALS
IN PLUMBING OF SATURN VEHICLES

REC Report 2643

This program is a development program involving proprietary concepts and components that have been developed and proven previous to this program and at the expense of Rosemount Engineering Company. The development being paid for by NASA consists of packaging the proprietary items to meet the rigid and difficult requirements set forth by NASA. Figure 1 shows, in a schematic manner, the packaging of the elements making up the complete sensor. The void areas in the unit are filled with Q-felt insulating material.

Proprietary Items. The proprietary item, referring to Figure 1, is the flow sensing element. This is considered proprietary as it was developed with Rosemount Engineering Company funds and offered for sale (REC Proposal 4650, 4 April 1963) previous to the issuance of this contract. Materials used, the manner in which they are processed, and the arrangement of these materials are considered proprietary as defined above and in General Provisions, NASA For 247 (1-63), Clause 24, Paragraph (i).

This flow sensing element can be used, with minor modification, to measure flow rates over any full scale range from 0 to 15 up to 0-15,000 or more standard cc/min. This element is suitable for use in most hydrocarbons; gaseous or liquid air, oxygen, nitrogen, hydrogen, helium, or hot-exhaust gases. The flow sensing element is a resistance changing device.

The volume meter was a NASA funded design and therefore is reported herein. The voltage regulator and the bridge are well known circuits made up of standard components. The heater control circuit may have some uniqueness in that it operates to -150°C. This control circuit, however, was devised by NASA personnel and not developed on this program by Rosemount Engineering Company, therefore, it will not be elaborated upon in this report.

Any other information regarding the unproprietary items are included on the enclosed specification drawing of the Leak Sensor 124D.

Flow Calibrator, Figure 2.

Principle. The principle of operation of the calibrator is based on volumetric displacement of water. A known quantity of the gas that is flowing through the sensor is collected and timed. Using this data, the volume flow rate in cc/min is obtained. Then by reading the barometric pressure and ambient temperature this data is converted to Standard cc/min.

Operation. Initially the solenoid valve is off allowing the gas flowing through the system to be exhausted into the atmosphere. The vent valve is opened, the pinchcock is closed and the water supply valve is opened. The flask, whose volume has been determined, is filled up to overflowing of the vent valve. The water valve and vent valve are closed and the pinch-cock opened. The water valve is again opened to allow the tube and the constant back pressure to fill up with water. The water valve is then closed. The solenoid valve is then energized allowing the gas to flow into the volume flask. Timing begins at this point. The output of the sensor is monitored and recorded. Timing is stopped when the water level reaches the reference line on the glass portion of the flask.

To control the inlet pressure of the gas, the operator uses a Moore regulator and sets the pressure using the Heise pressure gage that is built into the system. The metering valve is used to obtain various flow ratios.

The volume of the flask is determined by the following procedure. The operator fills up the tank as described before and then unhooks the tubing going into the constant back pressure head, opens the vent valve and drains the water into a preweighed container. The water is allowed to drain until the water level reaches the reference line. This volume of water is then weighed using a precision balance. The temperature of the water is measured and using the density of water at that temperature, the volume is calculated.

Constant back pressure head is obtained by adjusting the spill away level exactly in line with the predetermined reference mark on the glass tube.

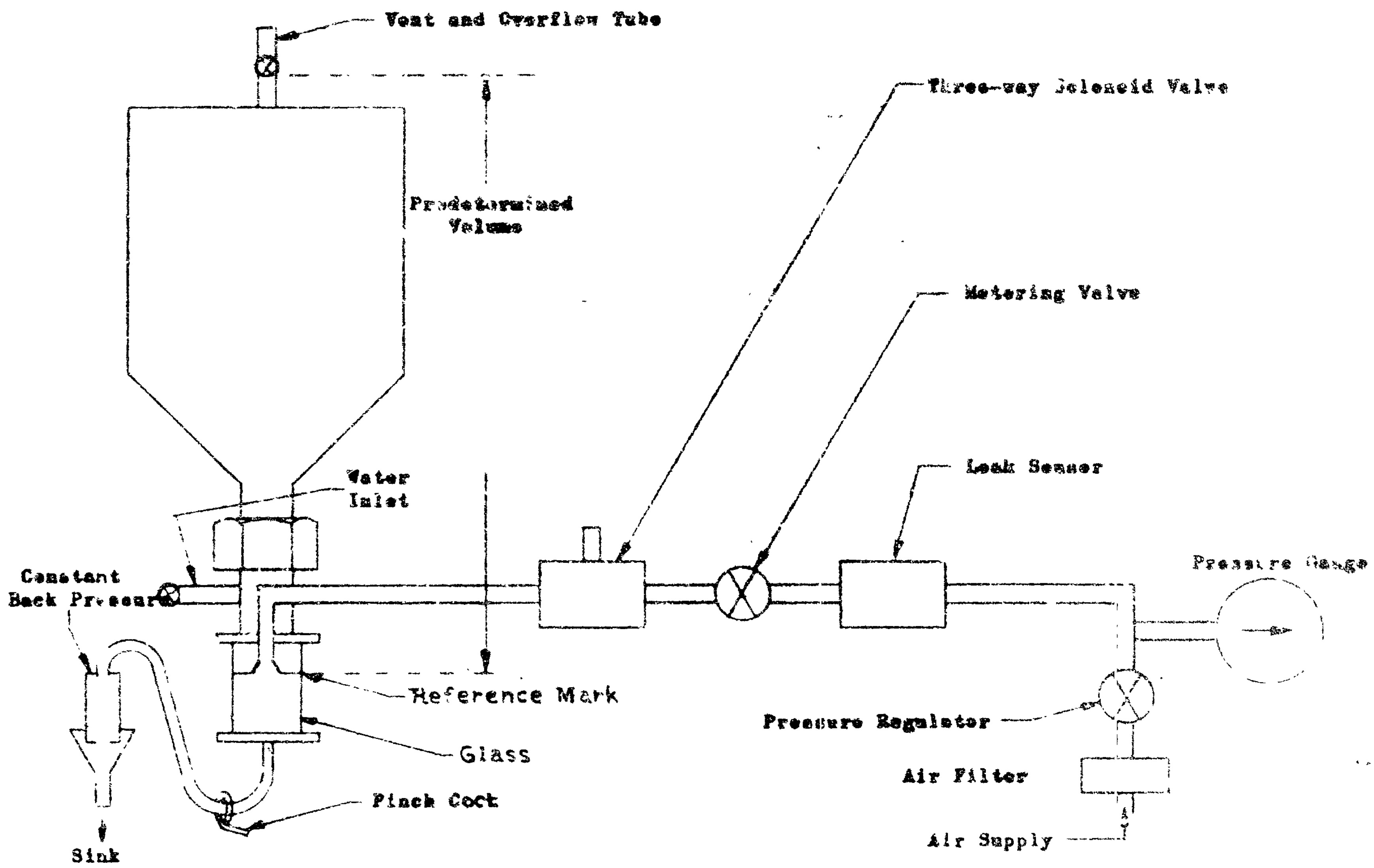


FIGURE 2

CALIBRATION SET UP FOR LEAK SENSORS

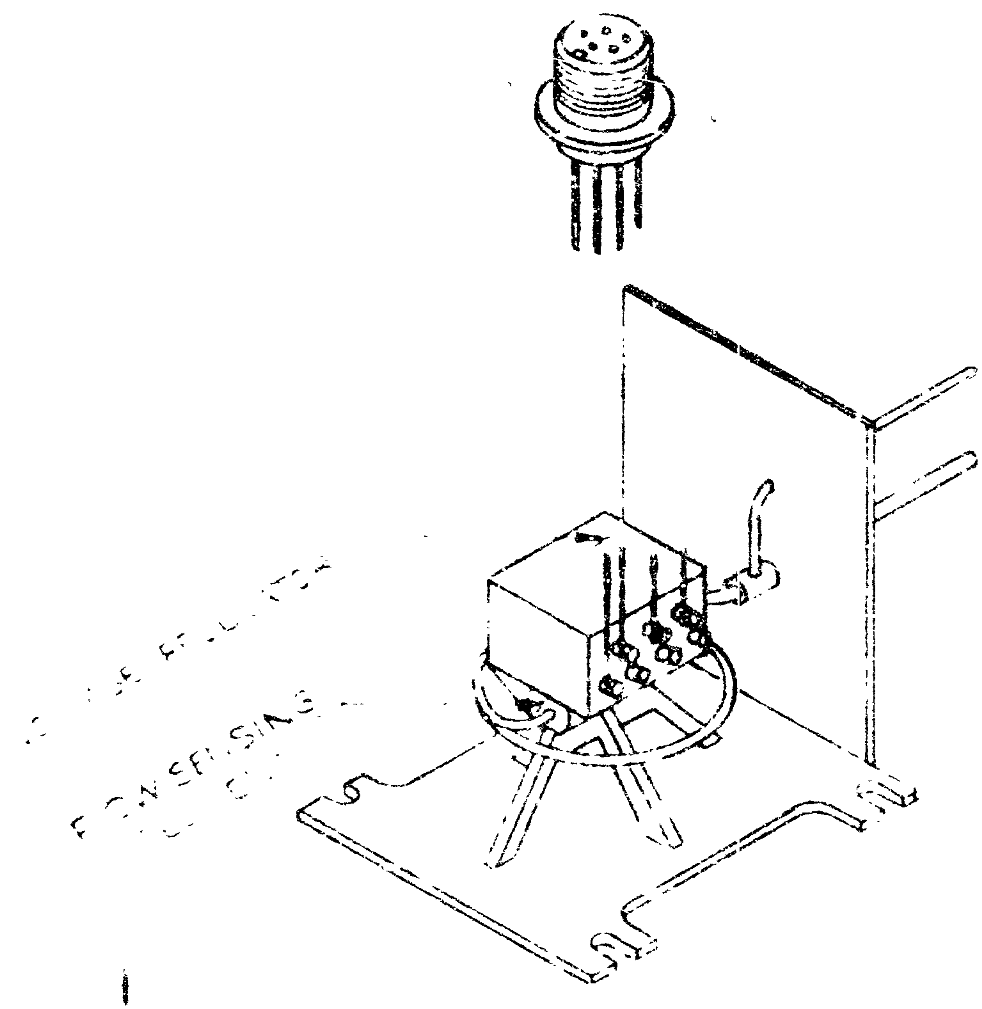


FIG. 1: INTERIOR CONSTRUCTION
HOT GAS LEAK SENSOR

SPECIFICATIONS

[illegible]

2. [illegible]

2.1. [illegible]

2.2. [illegible]

2.3. [illegible]

2.4. [illegible]

2.5. [illegible]

2.6. [illegible]

2.7. [illegible]

2.8. [illegible]

2.9. [illegible]

2.10. [illegible]

2.11. [illegible]

2.12. [illegible]

2.13. [illegible]

2.14. [illegible]

2.15. [illegible]

2.16. [illegible]

2.17. [illegible]

2.18. [illegible] at 50 volts DC.

3. [illegible]

TABLE I

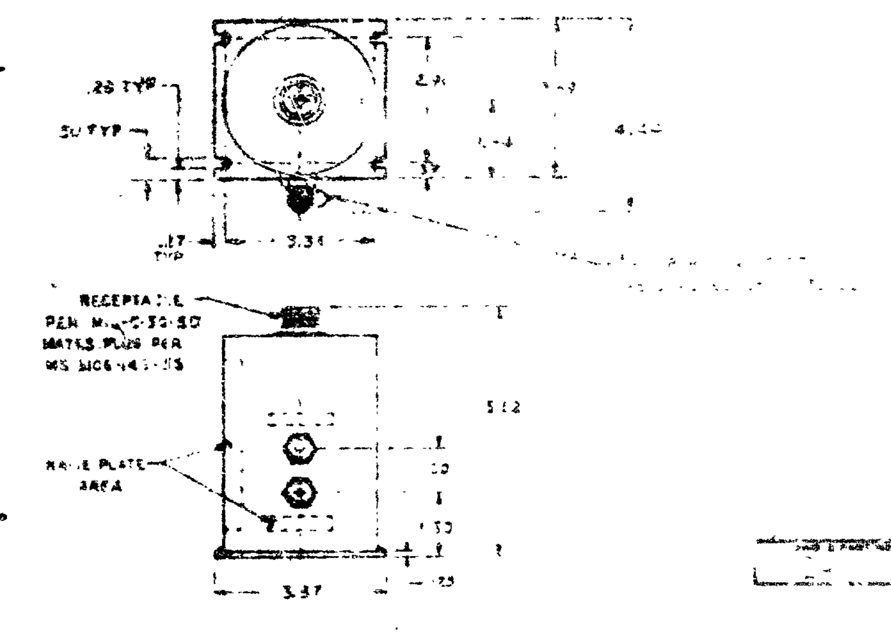
Flow Std. cc/min, Air	Output (Millivolts)	Interchangeability* (millivolts)
0	0	± 0.38
50	[illegible]	
100	3.4	
150	[illegible]	
200	[illegible]	± 0.38

TABLE II

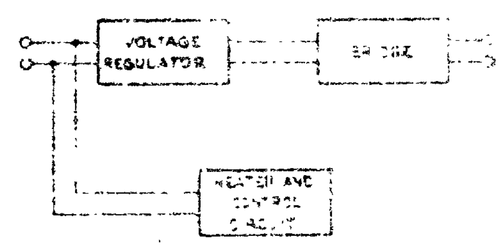
Flow Std. cc/min, Air	Output (Millivolts)	Interchangeability* (millivolts)
0	0	± [illegible]
[illegible]	5.5	
[illegible]	7.55	
[illegible]	[illegible]	
[illegible]	9.45	
1000	[illegible]	± [illegible]

*Interchangeability is defined for this purpose as [illegible]

REDUCED ONE HALF



PIN	DESIGNATION
A	-28 VDC IN
B	+28 VDC IN
C	-SIGNAL OUT
D	NEUTRAL
E	+SIGNAL OUT



SPECIFICATION DRAWING

THERMAL MASS FLOW SENSOR

ENGINEERING COMPANY

124 D